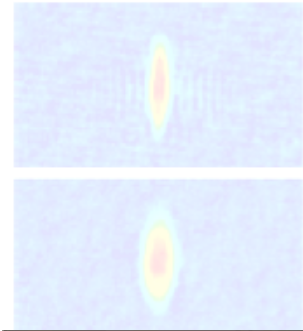


# azimuthally-sensitive femtoscopy and the energy scan program(s)

Mike Lisa

In collaboration with: E. Frodermann (U. Minn),  
M. Mitrovski, H. Petersen, M. Bleicher (Frankfurt)

# 100 years old & still smokin'



## NUCLEAR PHYSICS

### An afternoon's outing

Hidden in the yellowing pages of century-old issues of *Nature* are some scientific gems. They might be fully fledged 'Letters to the Editor', curiosities from 'Notes' or nuggets from 'Our Astronomical Column'. Even the simple listings in 'Diary of Societies', at the end of each issue, can be fascinating — as is this entry (pictured) from the issue of 17 June 1909.

At the behest of their boss, Ernest Rutherford, at the University of Manchester, Hans Geiger and Ernest Marsden had been conducting experiments on the scattering of  $\alpha$  particles from a thin gold foil. On that June afternoon — a century ago — they were to present to London's Royal Society their data "On the Diffuse Reflection of the  $\alpha$  Particles" (*Proc. R. Soc. A* **82**, 495–500; 1909).

The rest really is history. Geiger and Marsden had observed that, although most  $\alpha$  particles passed through the foil pretty much undeflected, very occasionally — and contrary to expectation — an  $\alpha$  particle could be scattered right back, through a very large angle. Rutherford had the interpretation: "the atom consists of a central charge supposed concentrated at a point", he wrote later (*Phil. Mag.* **21**, 669–688; 1911); the atom, far from being the 'plum pudding' that had been envisaged, had a nucleus.

Rutherford acknowledged that the essence of his nuclear model had been captured in the 'Saturnian atom' of Japanese physicist Hantaro Nagaoka (*Phil. Mag.* **7**, 445–455; 1904), "which he supposed consisted of a central attracting

compensation between the types of seasons in certain regions of the earth: H. Hildebrand **Hildebrandsson**.

---

**DIARY OF SOCIETIES.**

THURSDAY, JUNE 17.

ROYAL SOCIETY, at 4.30.—On the Origin of Certain Lines in the Spectrum of  $\epsilon$  Orionis (Alnitam): Sir Norman Lockyer, K.C.B., F.R.S., F. E. Baxandall, and C. P. Butler.—On Electrostatic Induction through Solid Insulators: Prof. H. A. Wilson, F.R.S.—The Effect of Pressure on the Band Spectra of the Fluorides of the Metals of the Alkaline Earths: R. Rossi.—The Ionisation produced by an  $\alpha$  Particle. Part I.: Dr. H. Geiger.—On the Diffuse Reflection of the  $\alpha$  Particles: Dr. H. Geiger and E. Marsden.—The Decay of Surface Waves produced by a Superposed Layer of Viscous Fluid: W. J. Harrison.—The Passage of Electricity through Gaseous Mixtures: E. M. Wellisch.—A Study of the Use of Photographic Plates for the Recording of Position: Dr. C. E. K. Mees.—The Coefficients of Capacity and the Mutual Attractions or Repulsions of Two Electrified Spherical Conductors when close together: Dr. Alexander Russell.—On the Effect of Previous Magnetic History on Magnetisation.—Prof. E. Wilson, G. F. O'Dell and H. W. K. Jennings.

LINNEAN SOCIETY, at 8.—On the Growth of a Species of *Battarea*: J. G. A. Tepper.—The Deposits in the Indian Ocean: Sir John Murray, K.C.B., F.R.S.—The *Sealark* Perseidea, Stenopidea, and Reptantia: L. A. Borradaile.—The *Sealark* Polychaeta. Part II.: F. A. Potts.—The *Sealark* Lepidoptera: T. Bainbridge Fletcher.—New Species of Malesian and Philippine Ferns: Dr. H. Christ.—The African Species of *Triumfetta*, Linn.: T. A. Sprague and J. Hutchinson.—The Acaulescent Species of *Malvastrum*: A. Gray and A. W. Hill.

ROYAL GEOGRAPHICAL SOCIETY, at 5.—Research Department. Annual Meeting.

FRIDAY, JUNE 18.

ROYAL INSTITUTION, at 9.—A Recent Visit to the Panama Canal: A. H. Savage Landon.

MONDAY, JUNE 21.

VICTORIA INSTITUTE, at 4.—Annual Meeting: Presidential Address by the Earl of Halsbury, F.R.S.

NO. 2068, VOL. 80]

[JUNE 17, 1909

*NATURE*

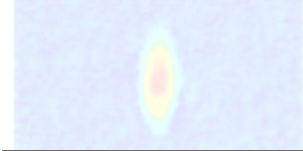
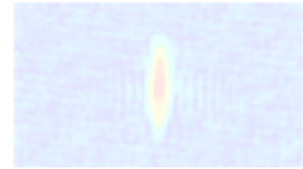
**Letters**  
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Univers  
Societie  
Diary o

mass surrounded by rings of rotating electrons". But it was these data from Geiger and Marsden in 1909, and those that followed, that enabled the detail of the structure of the atom to be drawn more

accurately than ever before. The nucleus was revealed, and a century of nuclear physics began.

ALISON WRIGHT

# 100 years old & still smokin'



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[JUNE 17, 1909

NATURE

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ALISON WRIGHT

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## NUCLEAR PHYSICS

In her lifetime...

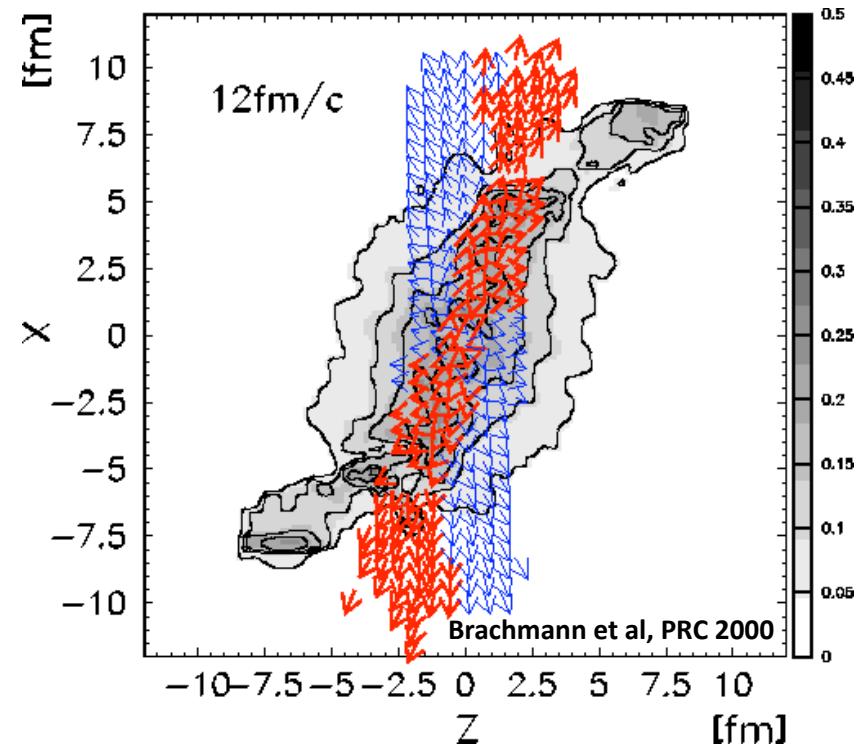
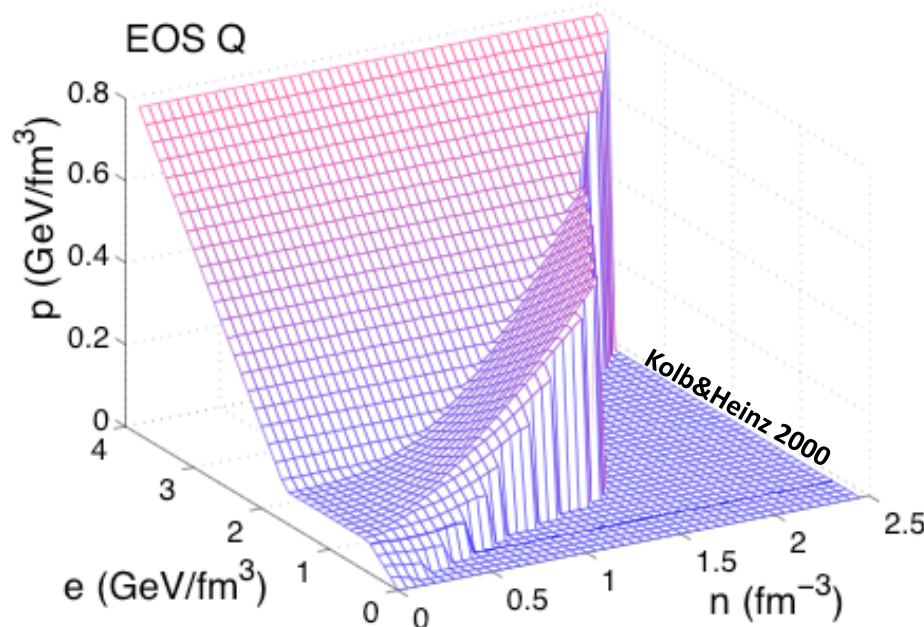
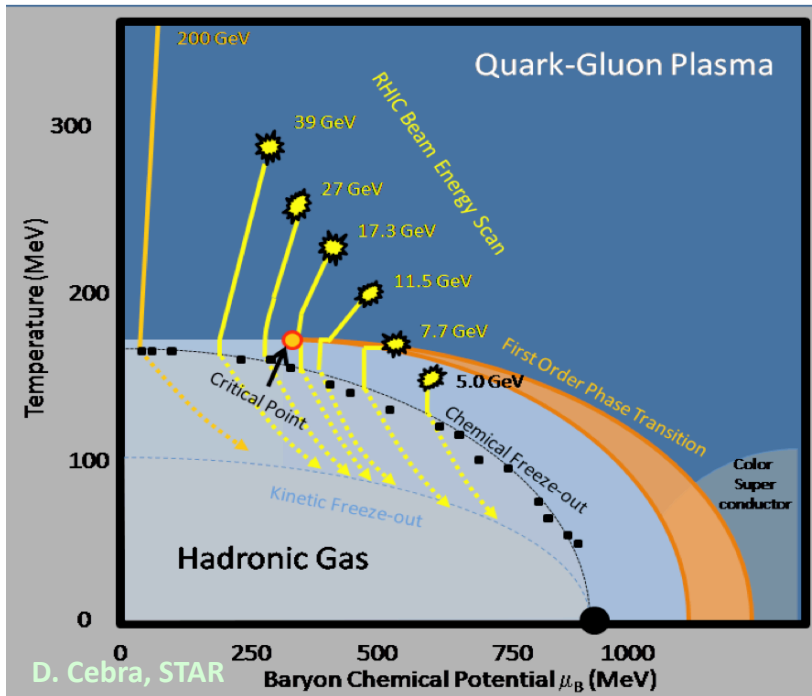
- existence of nucleus
- structure of nucleus (protons...)
- symmetry/group-theory based substructure of hadrons (quarks: flavor, color)
- dynamic substructure of hadrons (partons)
- complex and unique theory of partons interactions (QCD; confinement; asymptotic freedom)
- theoretical & experimental exploration of QCD **phases** (QCD, chiral FT, RHIC energy scan)
- (and airplanes and computers and stuff...)



# dynamic studies

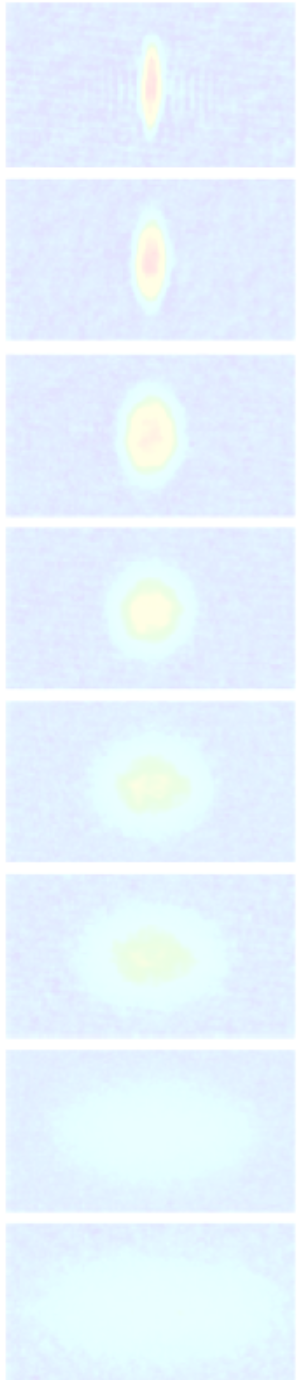
Probe QCD phase diagram via

- statistics/fluctuations
- ✓ dynamic system response
  - transport models (phase structure in EoS)
  - bulk collectivity (low- $p_T$  measurements)

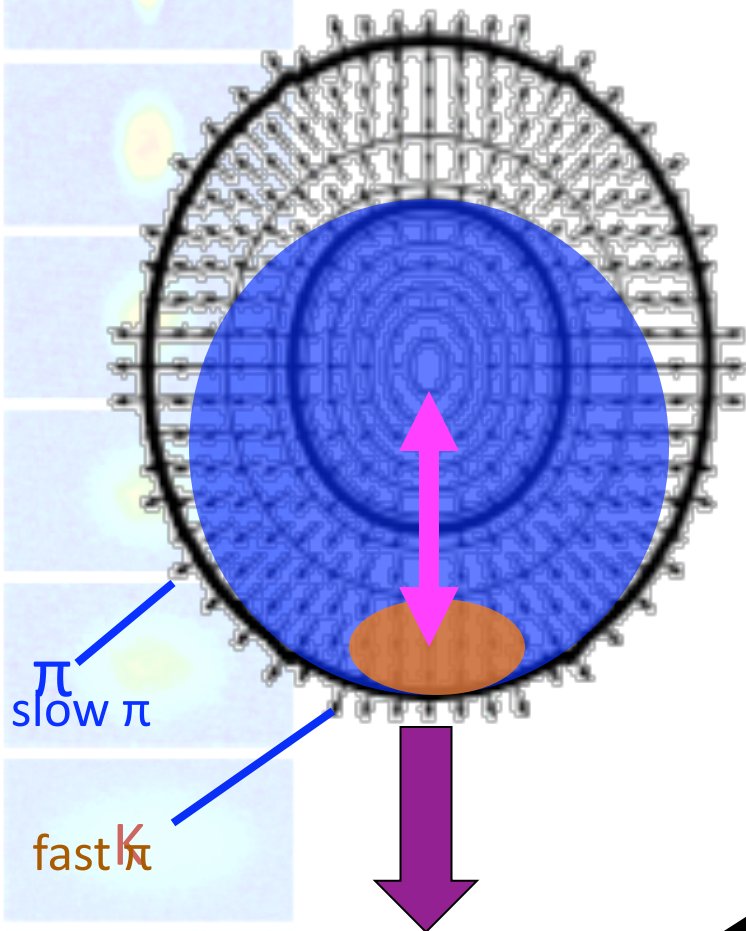


# Outline

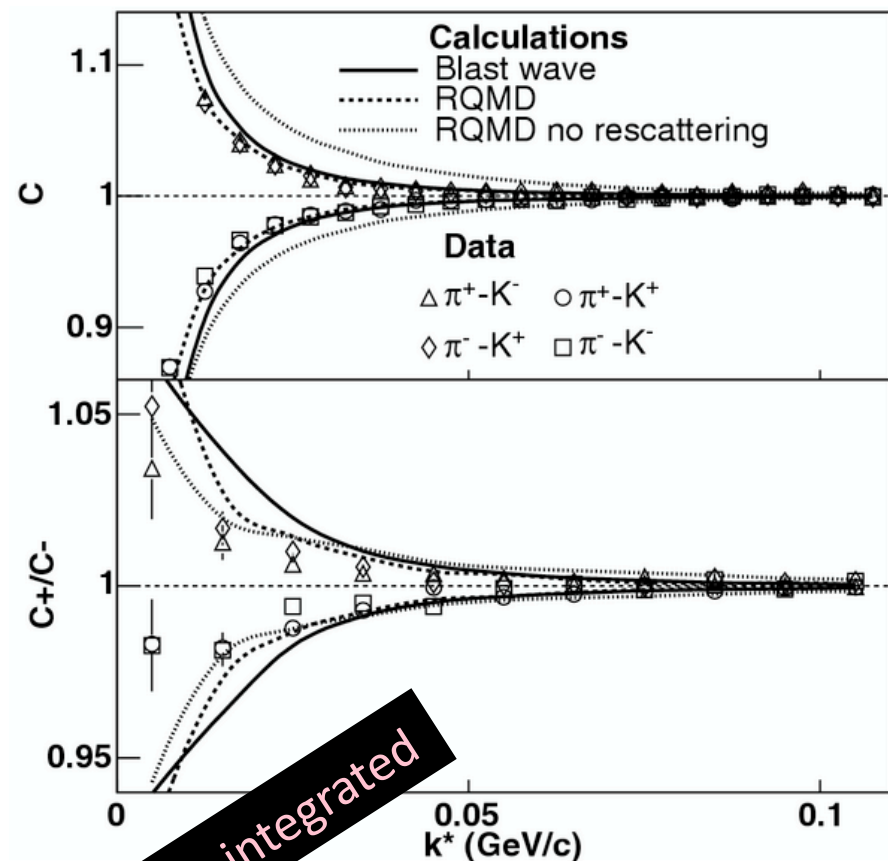
- femtoscopy (HBT) and collectivity in R.H.I.C.
  - radial, longitudinal, **directed, elliptic**
- azimuthally-sensitive HBT (asHBT)
  - what is measured
  - what it measures
  - what's been measured
- model calculations
  - 2D hydro
  - RQMD, UrQMD
  - 3D hydro + UrQMD



Explosive flow revealed through *specific fingerprints* on soft-sector observables calculable in hydro or toy “blast” models



*defining* characteristic: correlated position and boost direction



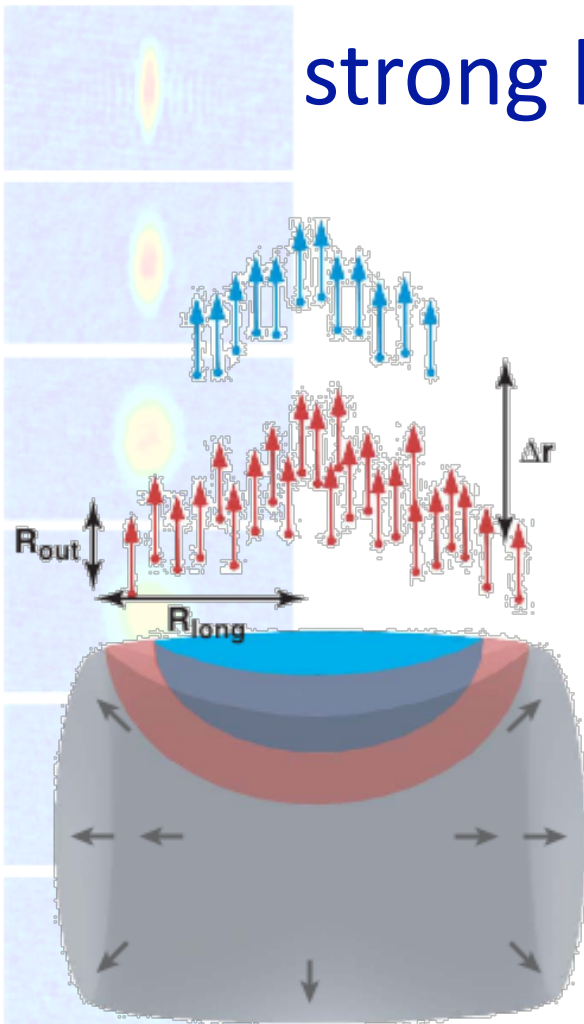
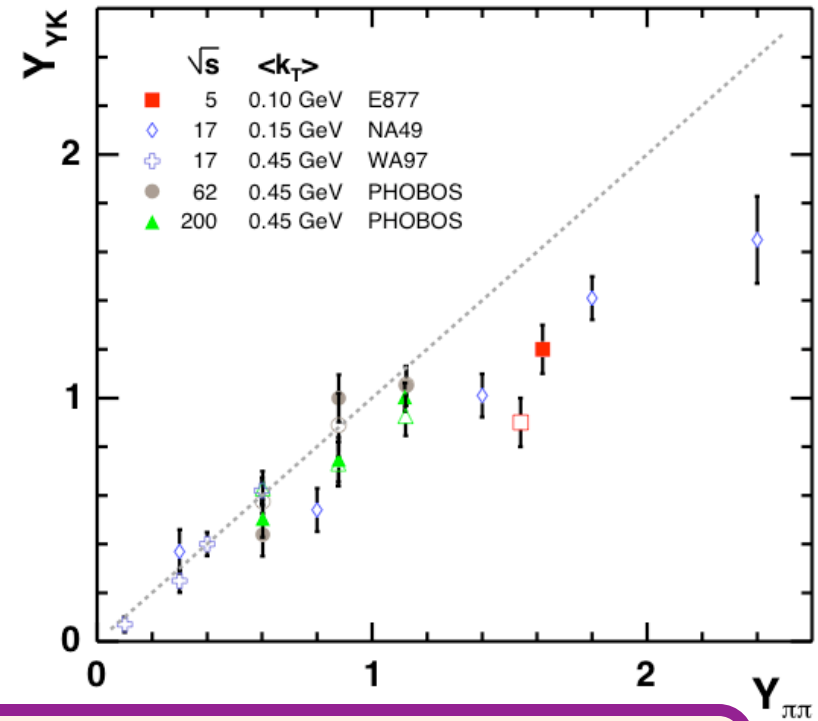
STAR PR1 91 262301 (2003)

transverse, azimuthally-integrated

space-momentum substructure mapped *in detail*

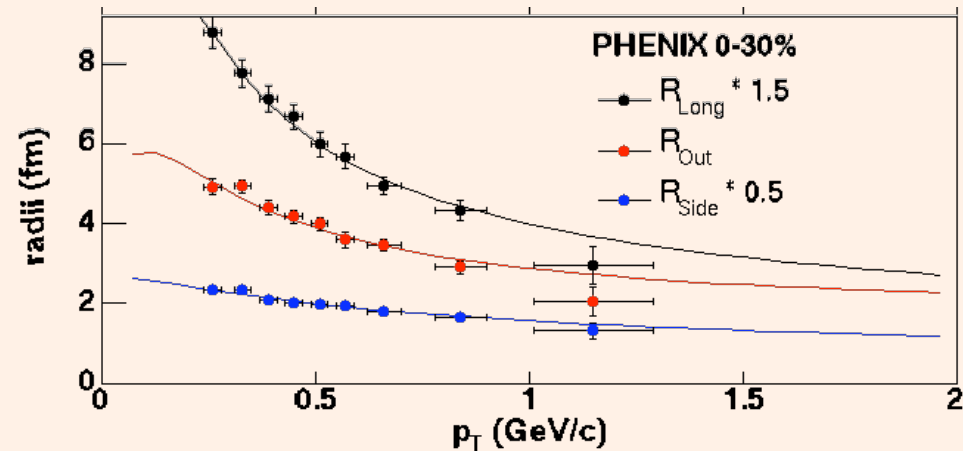
# strong longitudinal flow (not necc B.I.)

Ann Rev Nucl Part Sci (2005) nucl-ex/0505014

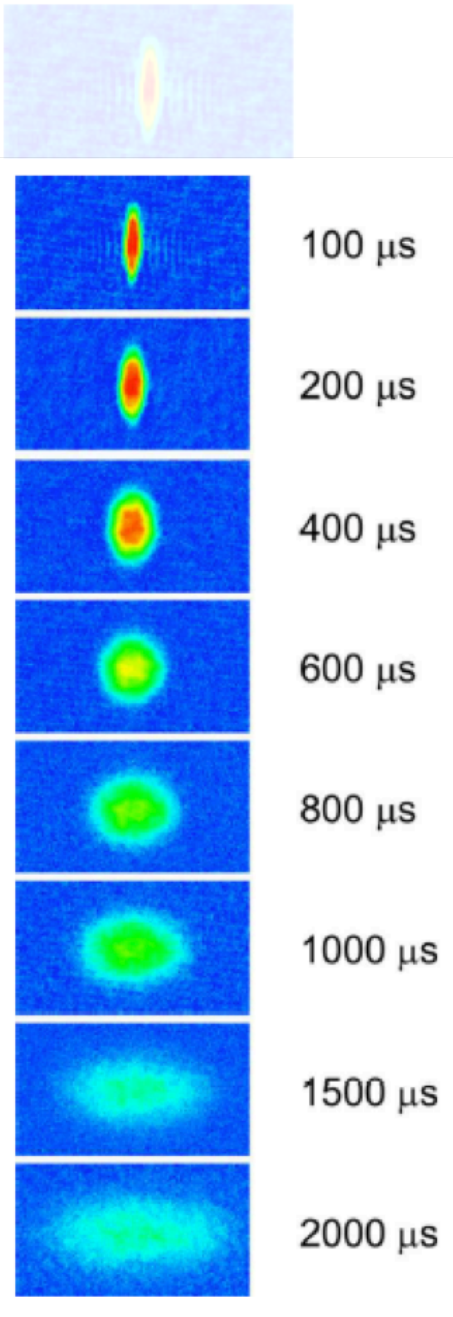


Also:  $R_{ol}^2(y, p_T)$

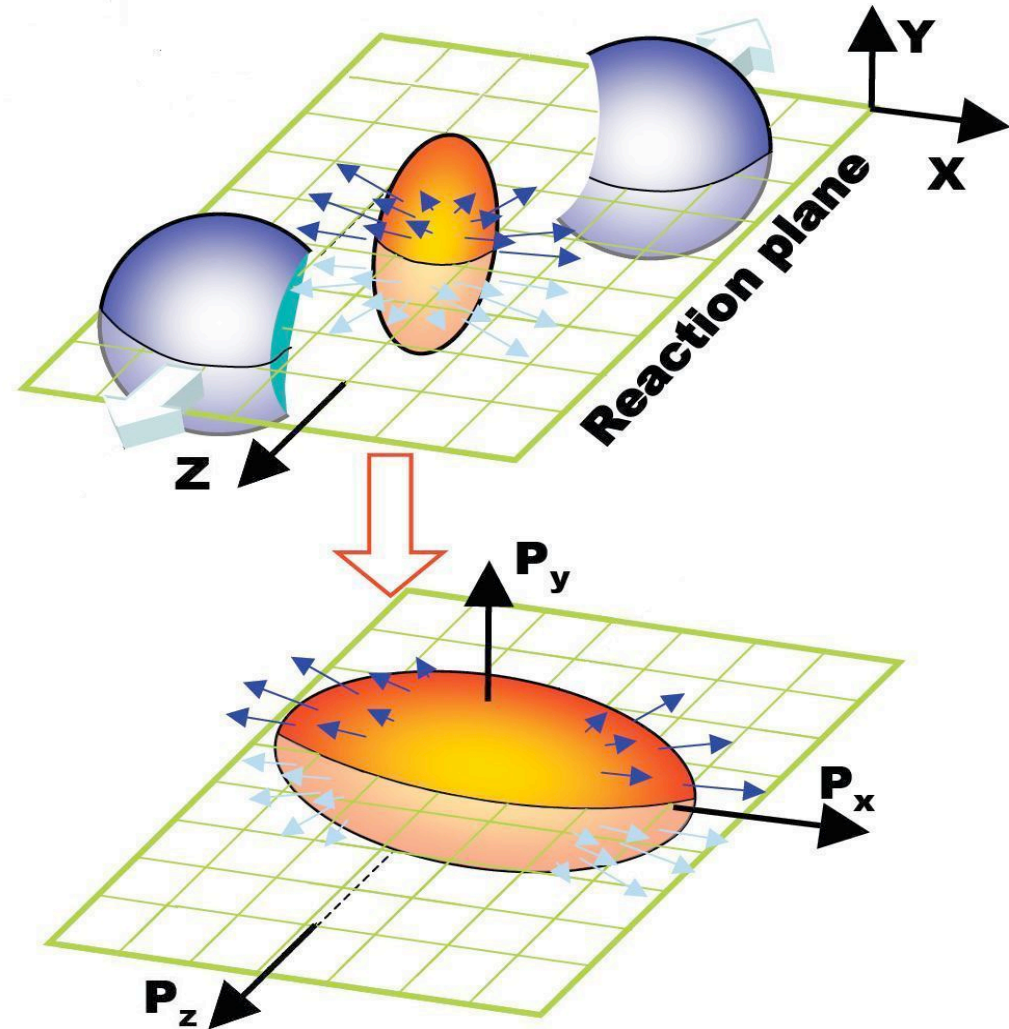
less attention to longitudinal d.o.f. in HBT



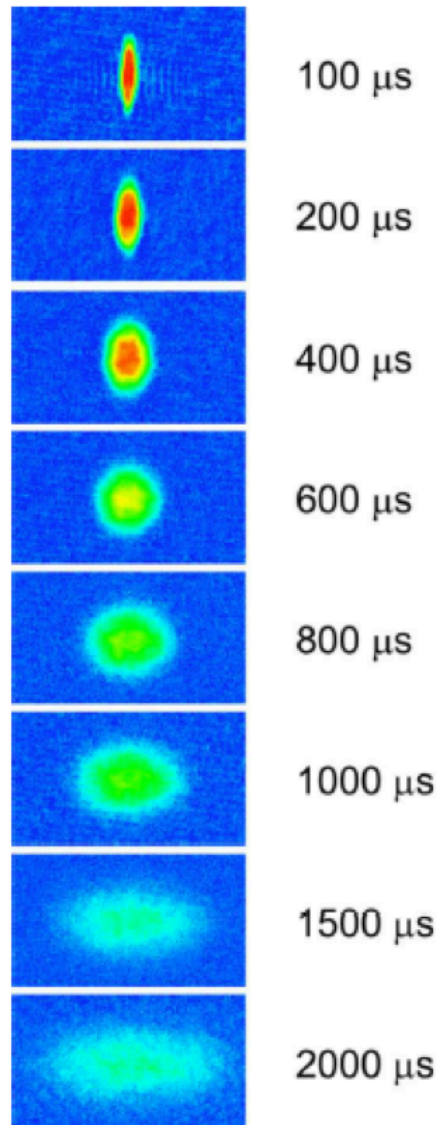
# phi- the sexy direction



O'Hara et al, *Science* 2002

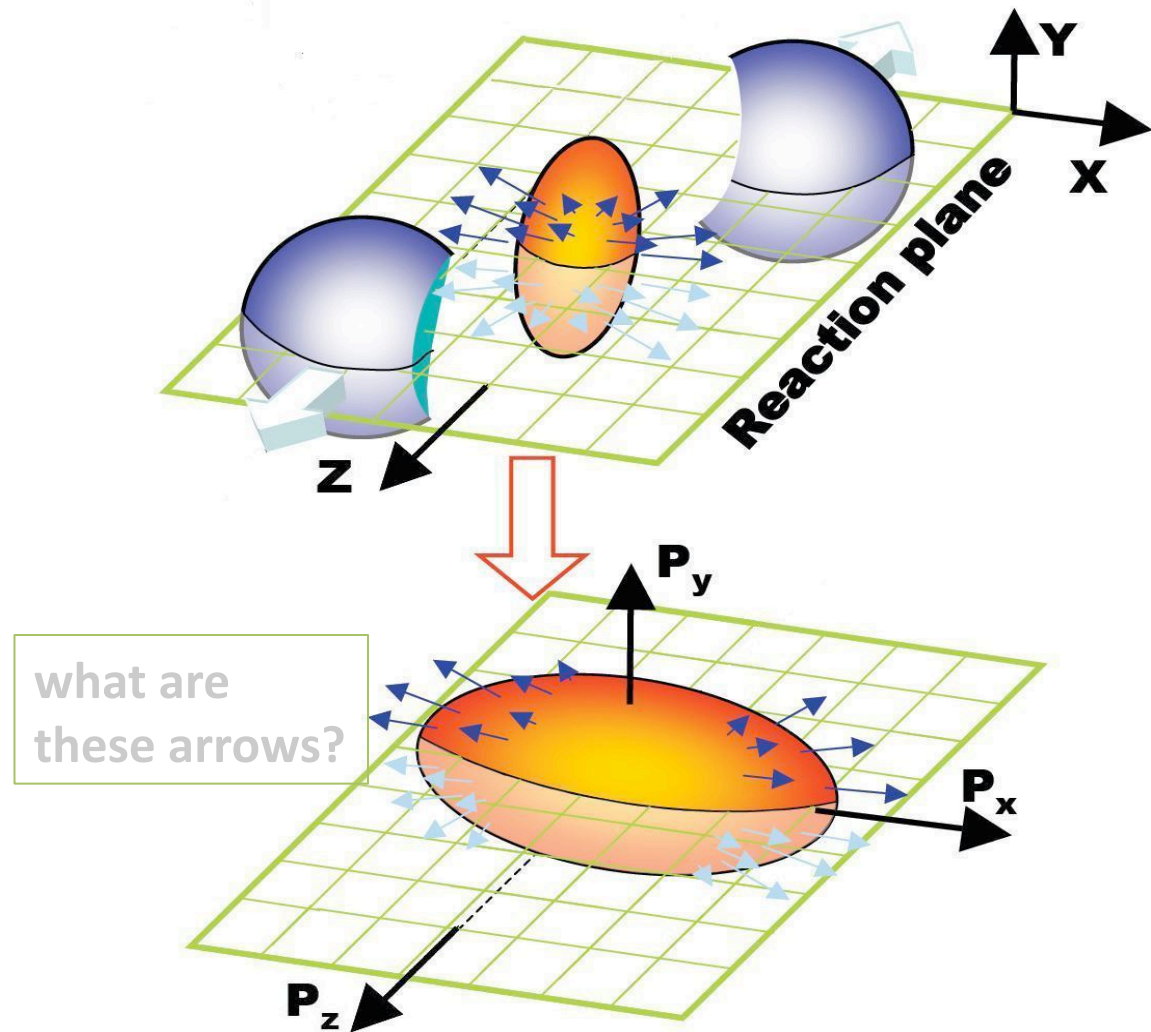


this is *space*



O'Hara et al, *Science* 2002

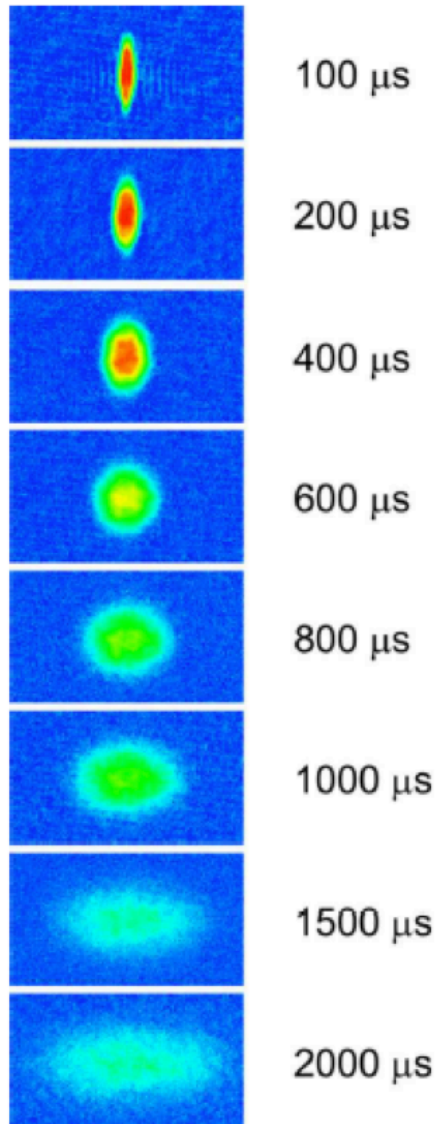
phi- the sexy direction



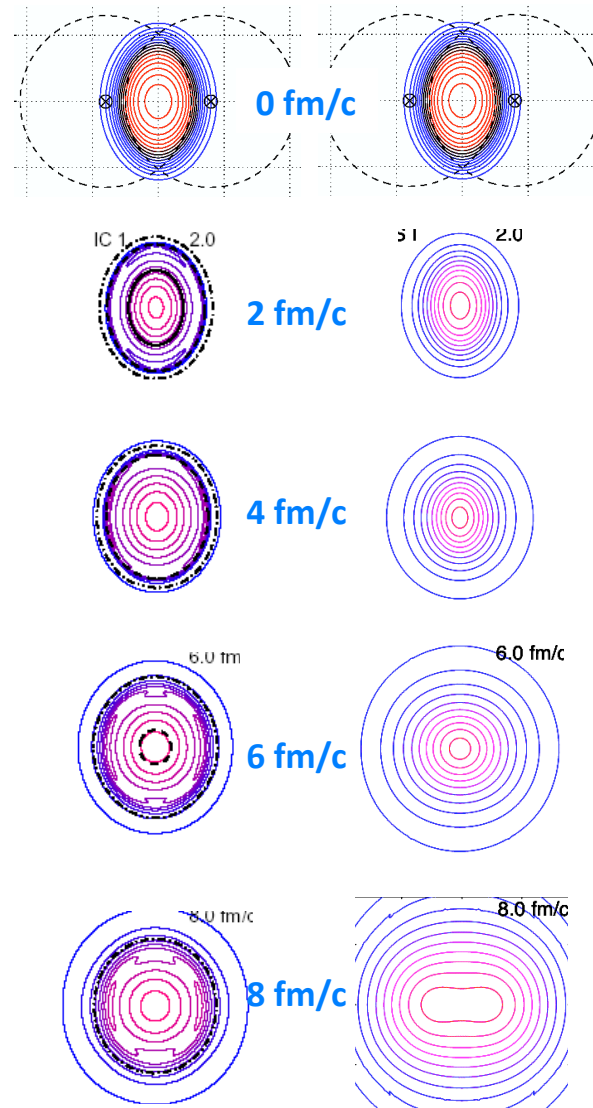
ultra-cold atoms

ultra-hot partons

# phi- the sexy direction



O'Hara et al, *Science* 2002



P. Kolb, PhD 2002

evolution from initial “known”  
shape depends on

- pressure anisotropy (“stiffness”)
- lifetime \*

\* O'Hara could *choose* when to  
destroy his system

# phi- the sexy direction

evolution from initial “known” shape depends on

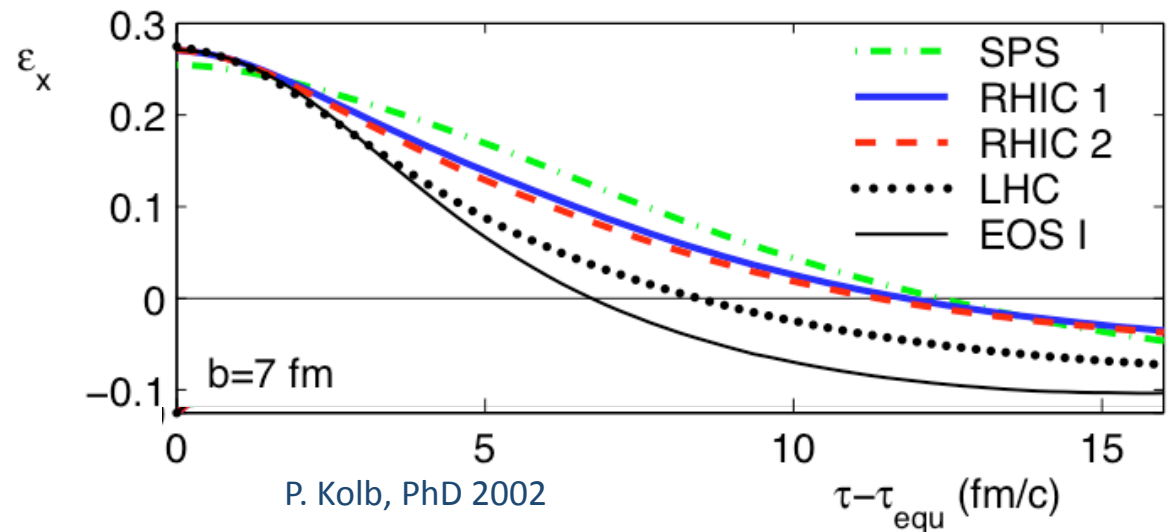
- pressure anisotropy (“stiffness”)
- lifetime

Both are interesting!

We will measure a convolution over freezeout

- model needed

$$\varepsilon \equiv \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

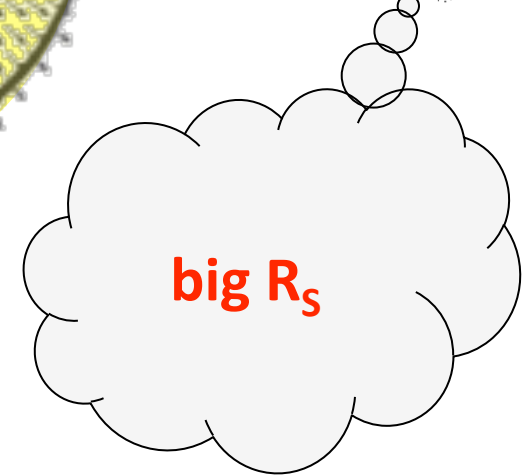
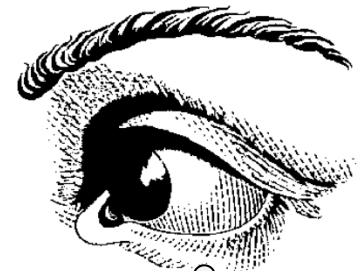
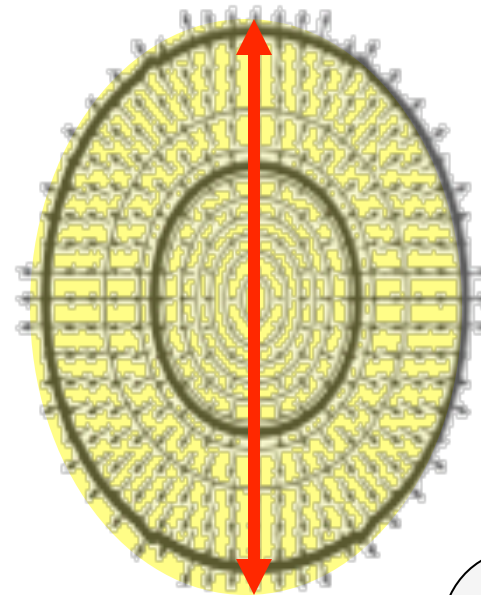
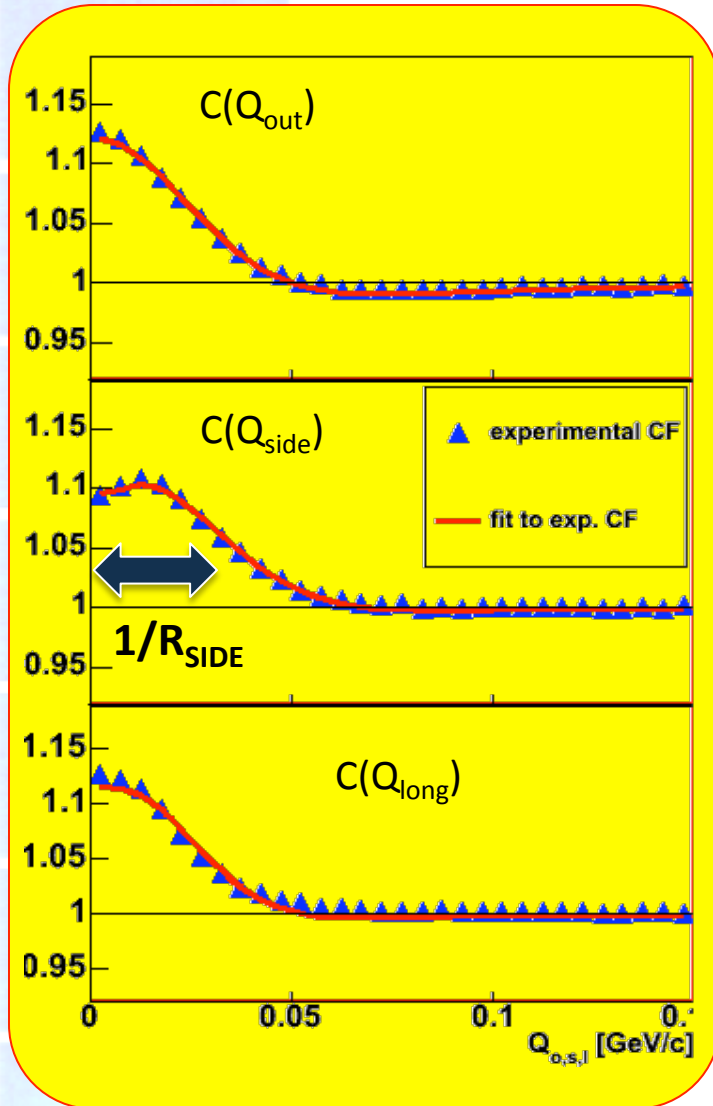


P. Kolb, PhD 2002

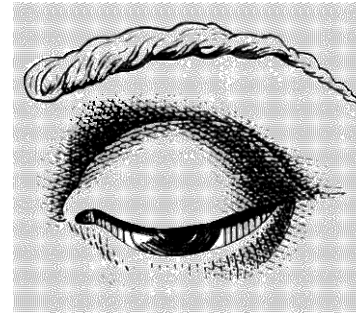
# measuring lengths

$$C(\vec{q}) = N \cdot \left[ 1 + \lambda \cdot \left( K_{coul}(\vec{q}) \cdot \left\{ 1 + e^{-\left( q_o^2 R_o^2 + q_s^2 R_s^2 + q_l^2 R_l^2 \right)} \right\} - 1 \right) \right]$$

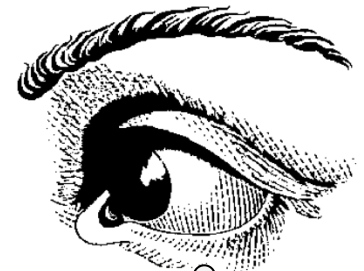
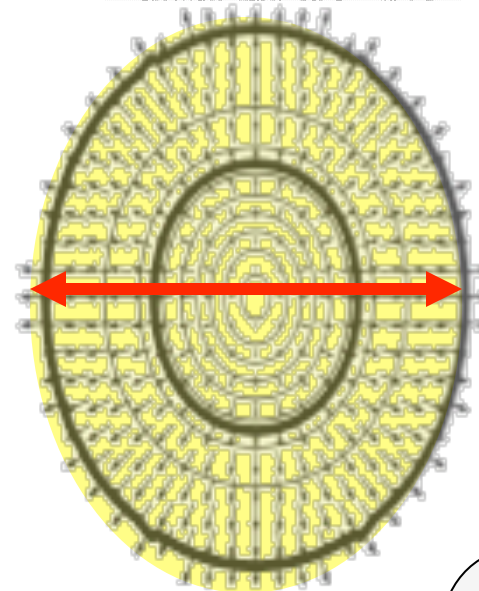
typical "Gaussian" fitting function



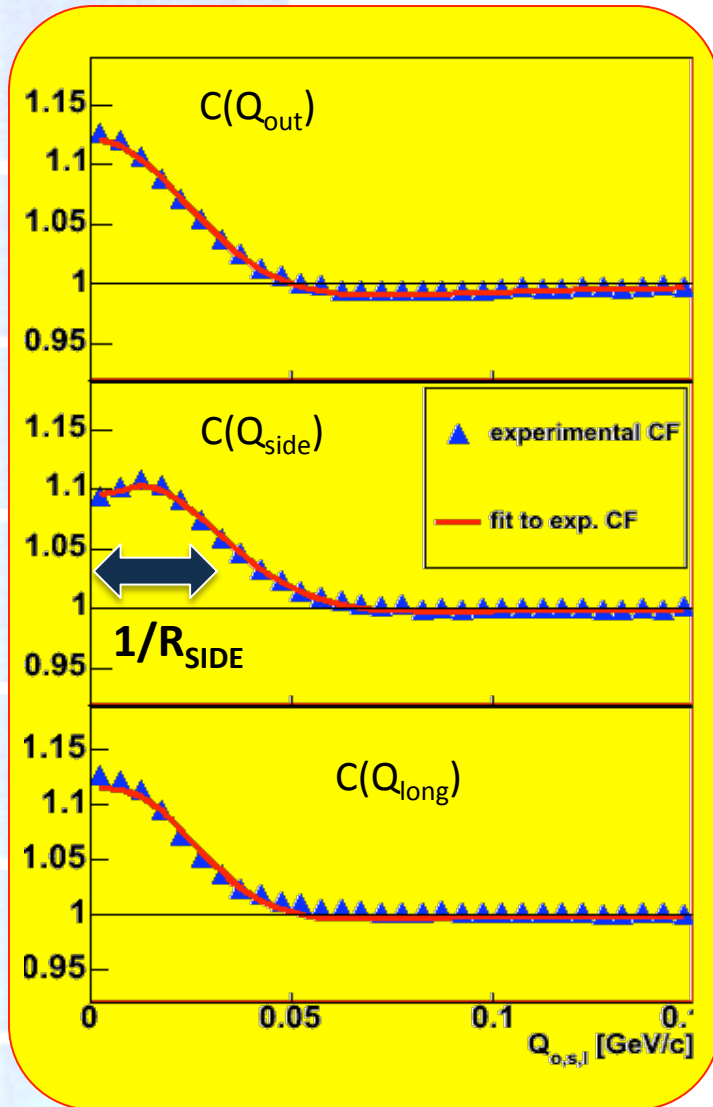
# measuring shape



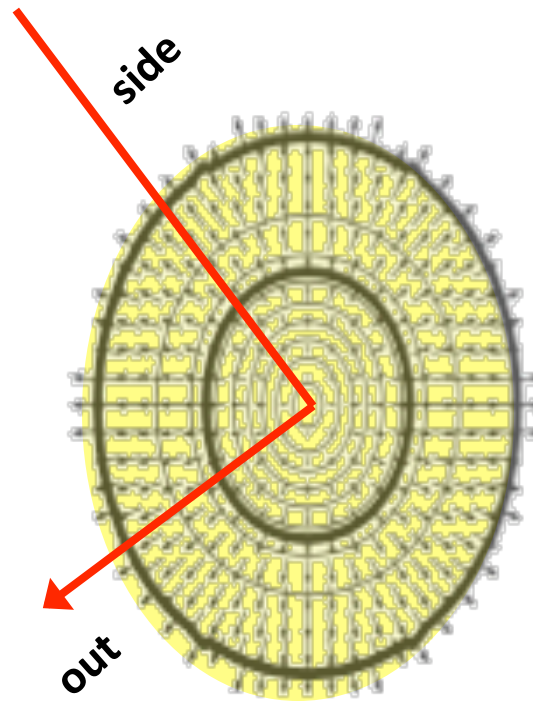
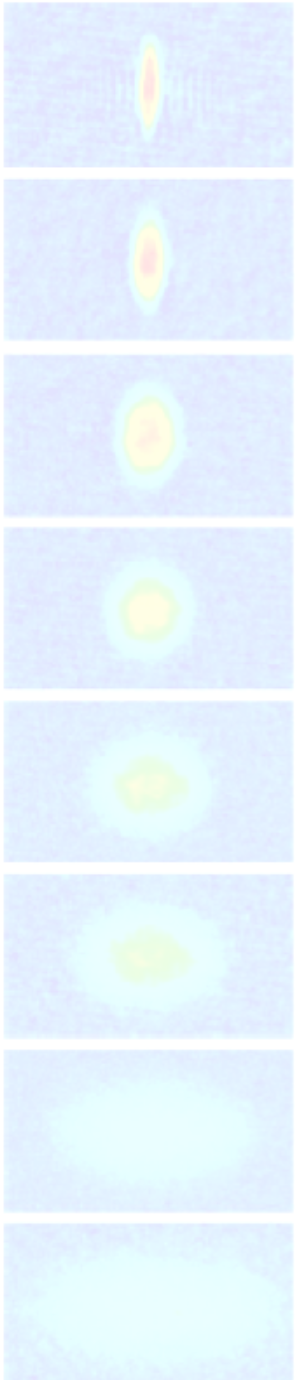
small  $R_s$



big  $R_s$



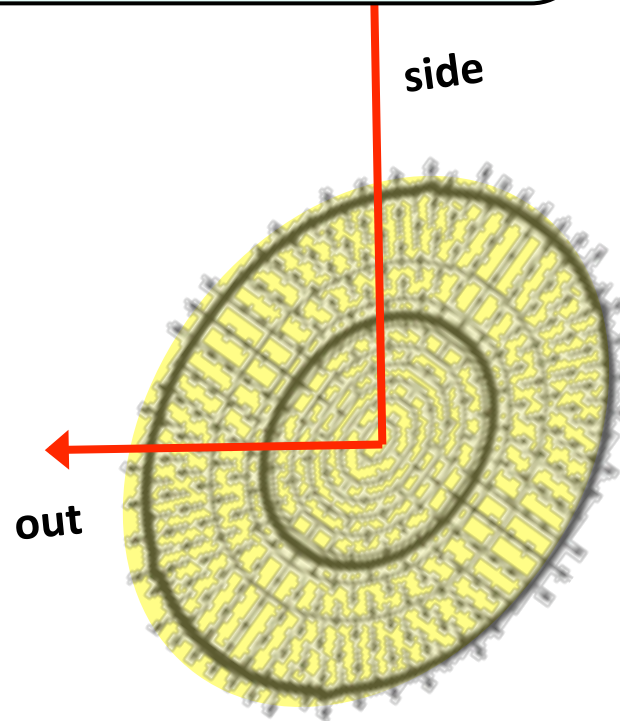
# measuring shape



# measuring shape

$$C(\vec{q}) = N \cdot \left[ 1 + \lambda \cdot \left( K_{coul}(\vec{q}) \cdot \left\{ 1 + \exp(-q_i q_j R_{ij}^2) \right\} - 1 \right) \right]$$

more info. **six** “HBT radii”  $R_o^2, R_s^2, R_l^2, R_{os}^2, R_{sl}^2, R_{ol}^2$

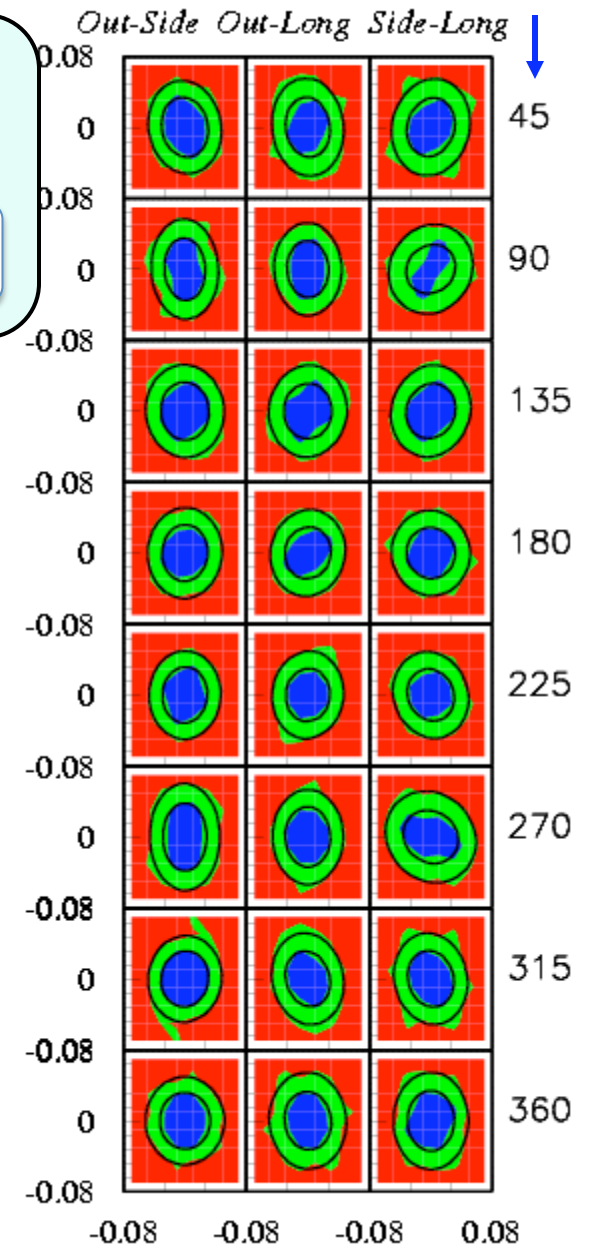
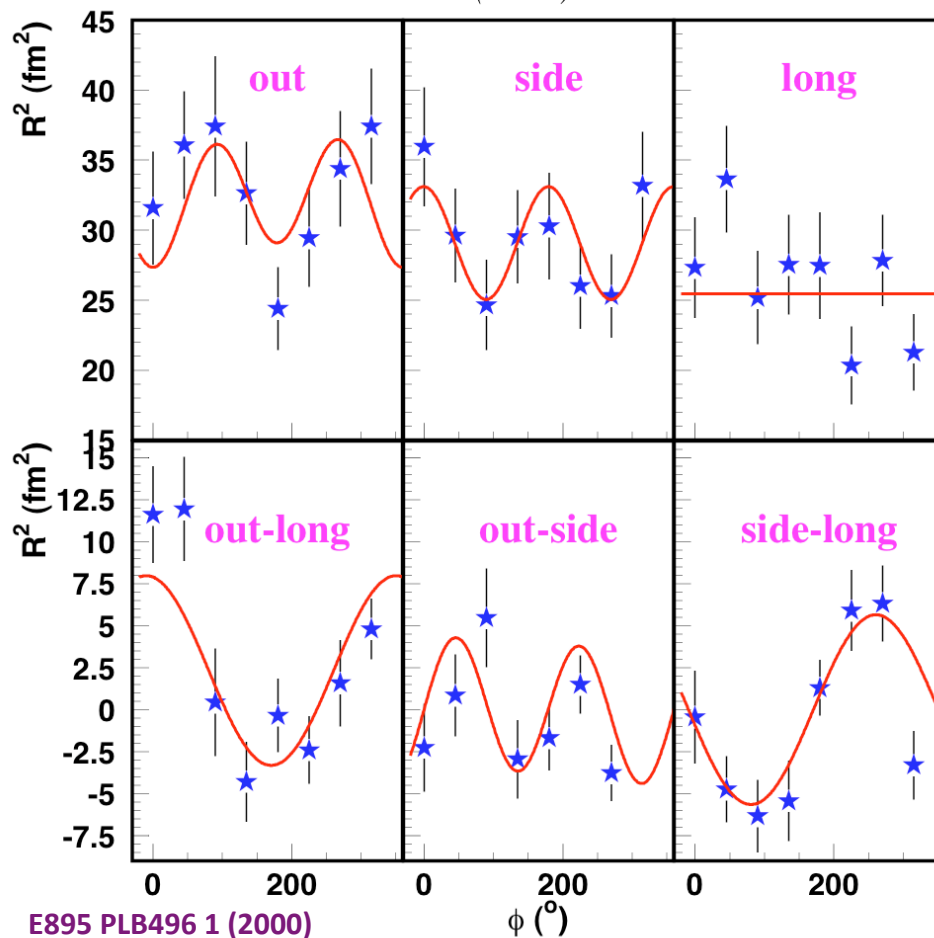


$R_{out-side}^2 < 0$

# measuring shape

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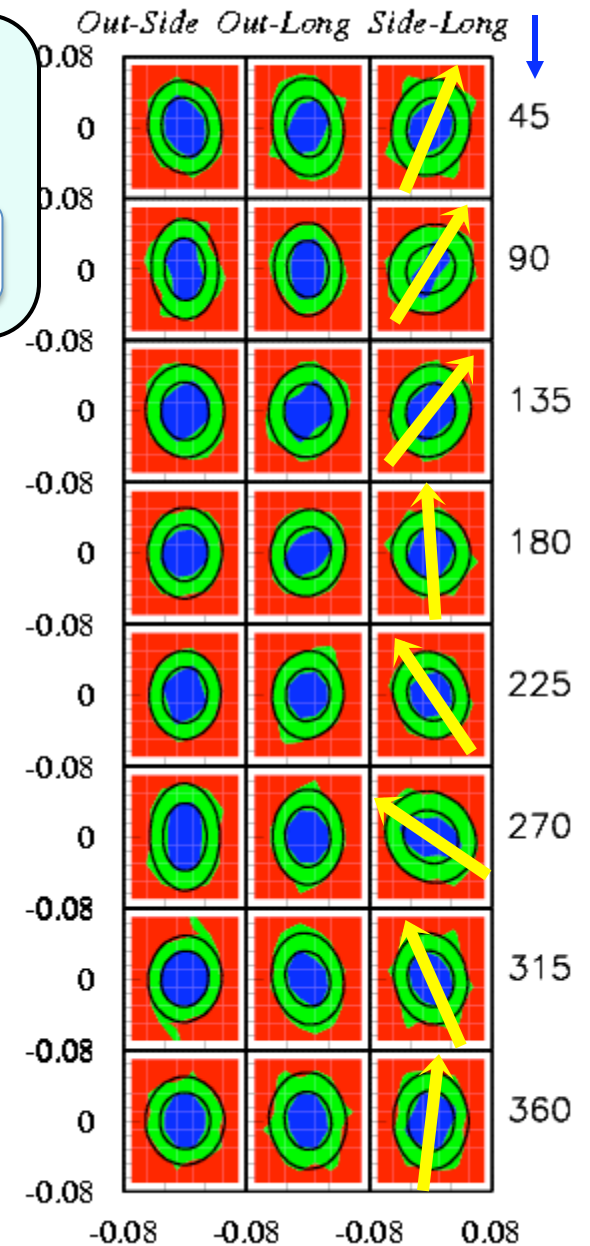
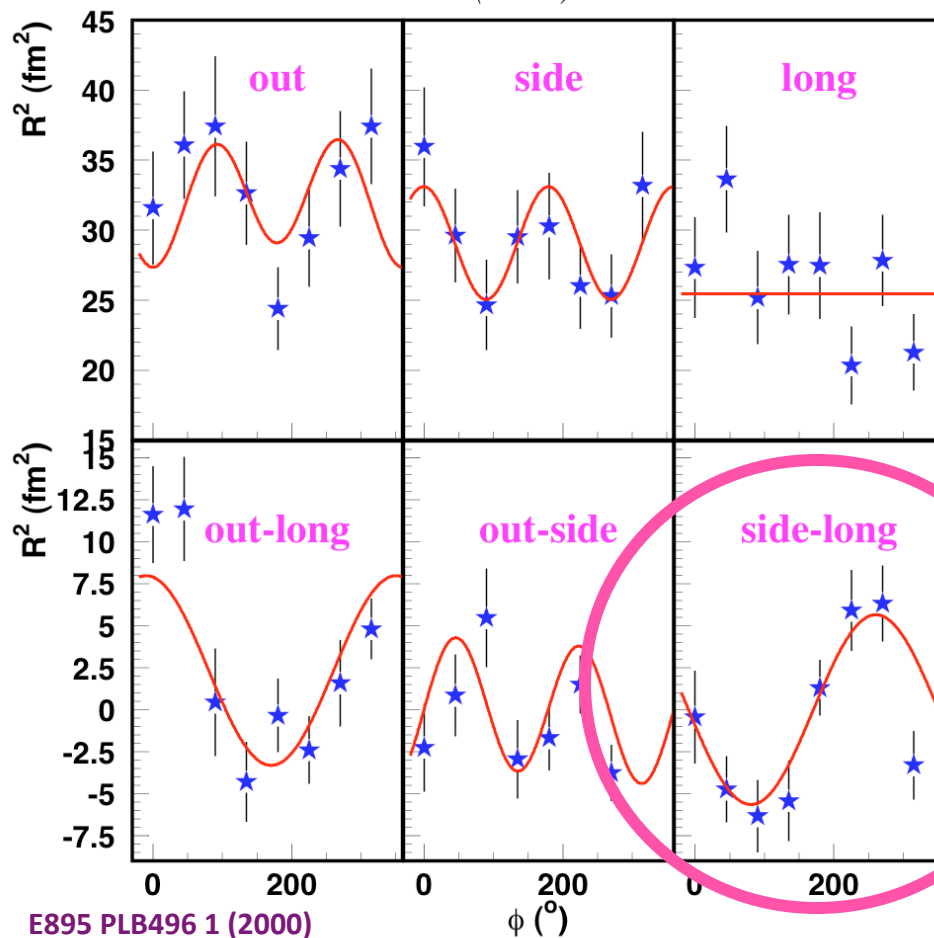


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more info. **six** “HBT radii”

$$R_o^2, R_s^2, R_l^2, R_{os}^2, R_{sl}^2, R_{ol}^2$$



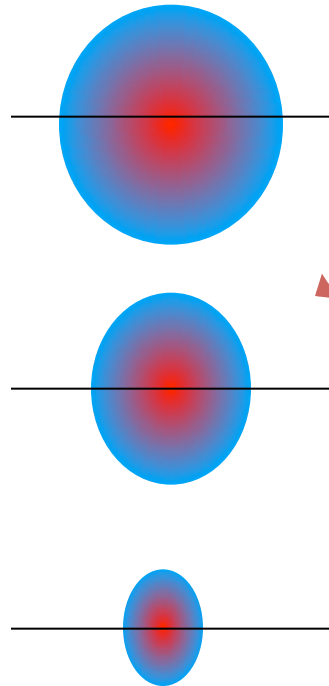
# expected systematics



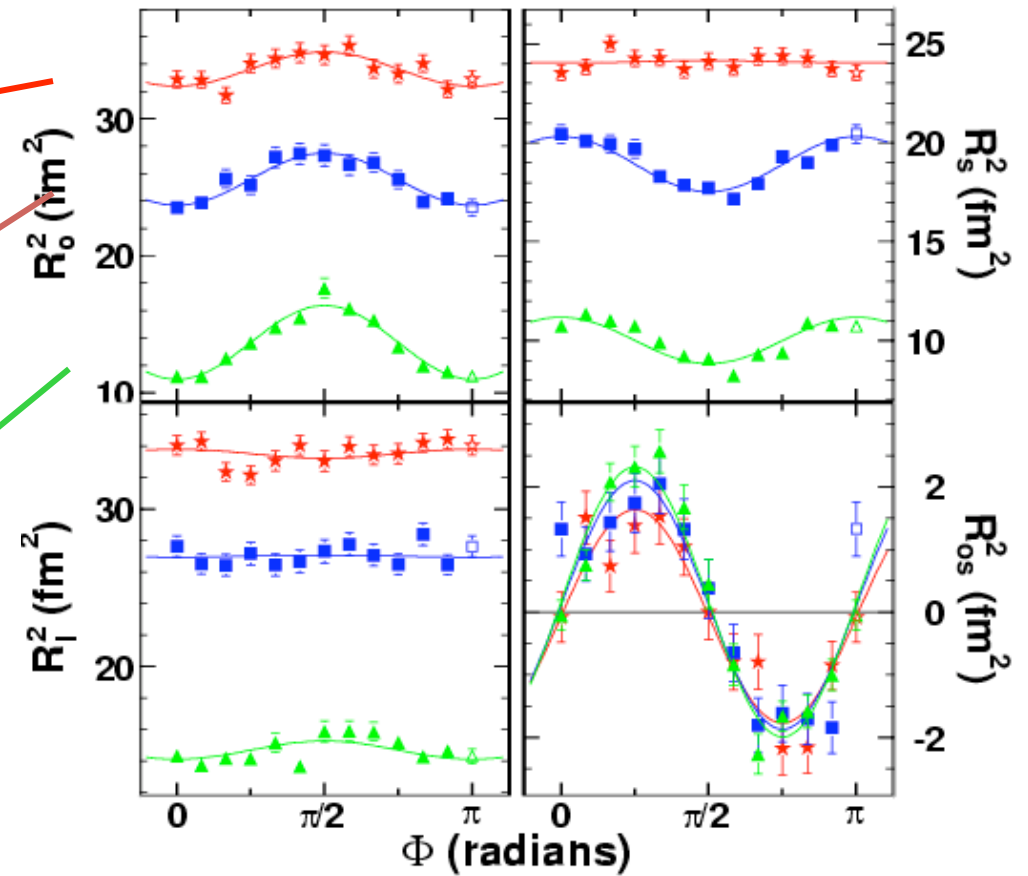
central  
collisions

mid-central  
collisions

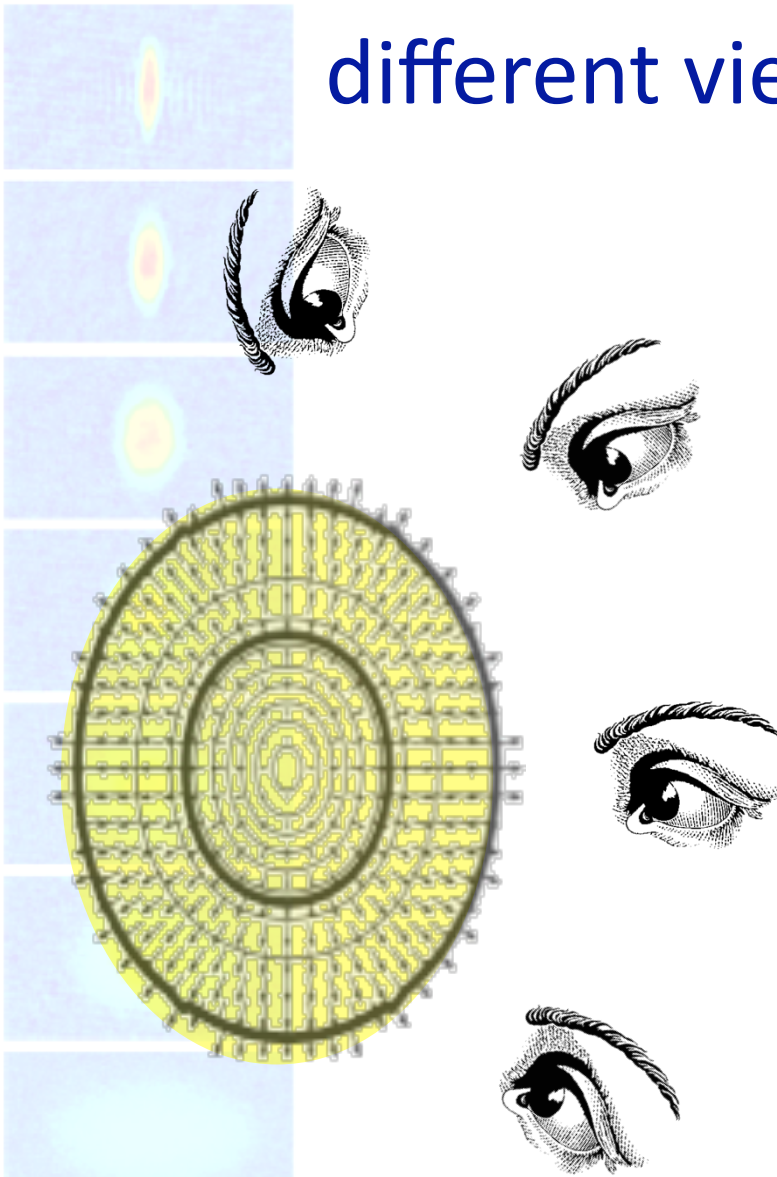
peripheral  
collisions



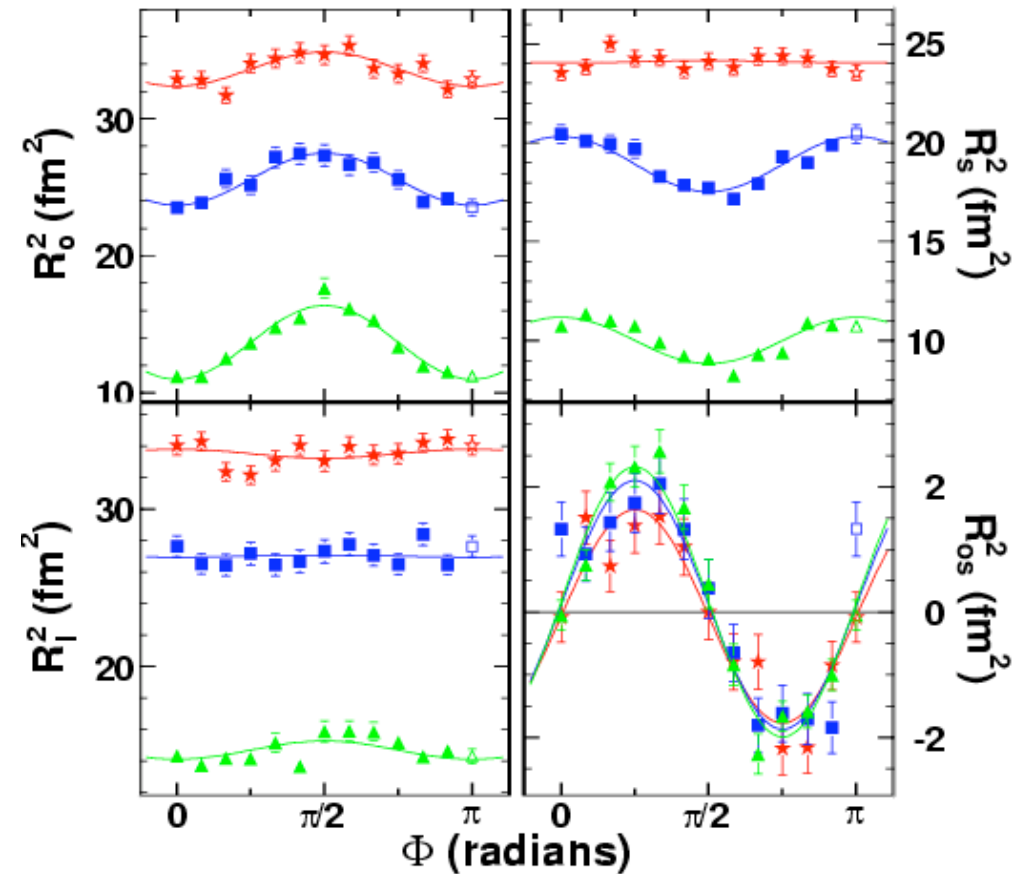
STAR, PRL93 012301 (2004)



# different views of the “same” source?



STAR, PRL93 012301 (2004)

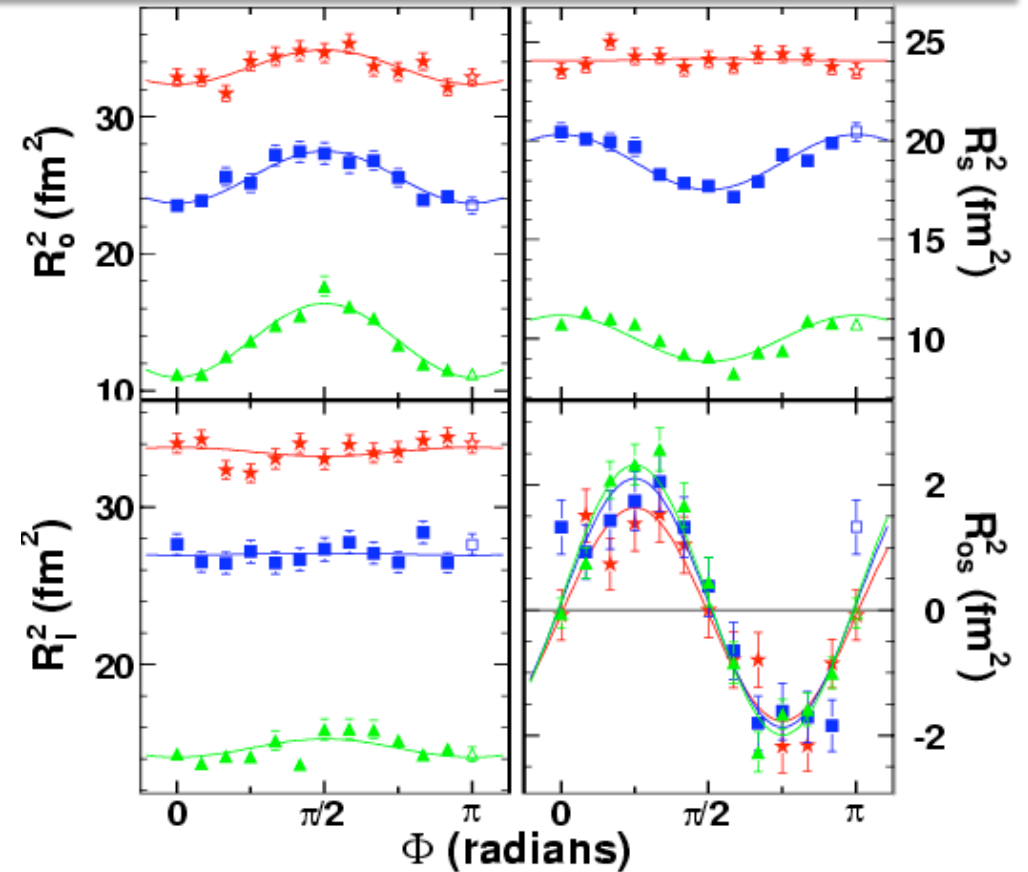
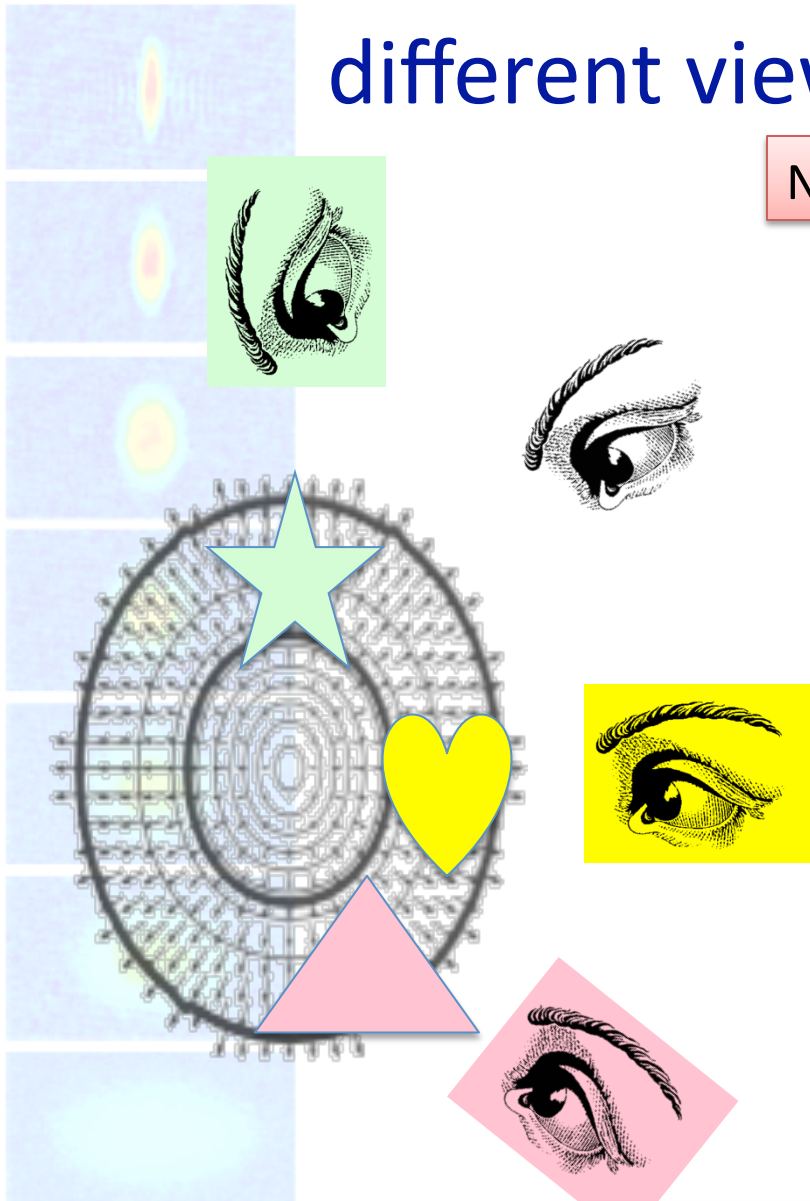


$$R_{s,n}^2 \equiv \langle R_s^2(\phi) \cdot \cos(n\phi) \rangle \quad \varepsilon = 2 \frac{R_{s,2}^2}{R_{s,0}^2} = 2 \frac{R_{os,2}^2}{R_{s,0}^2} = -2 \frac{R_{o,2}^2}{R_{s,0}^2}$$

Retiere&MAL PRC70 (2004) 044907

# different views of the “same” source?

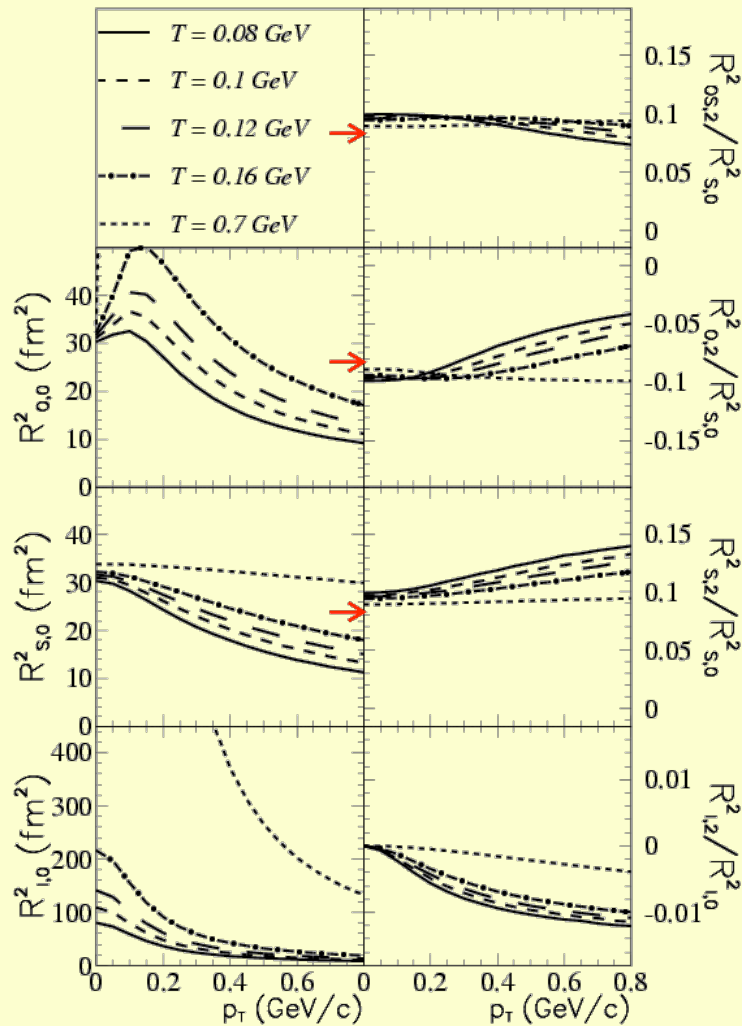
No! Homogeneity regions can be totally different!



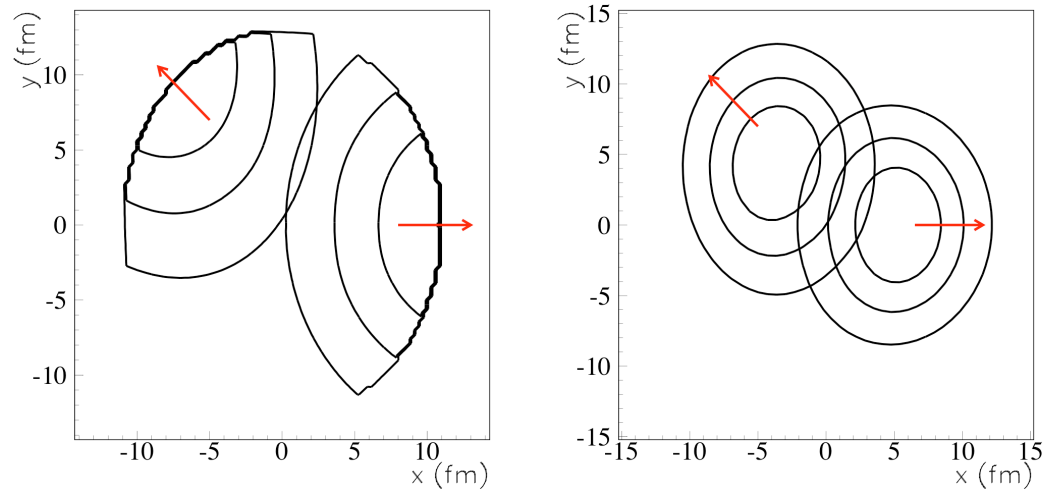
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Retiere&MAL PRC70 (2004) 044907

# BW: “typical” model of flow-induced substructure



## Blast Wave



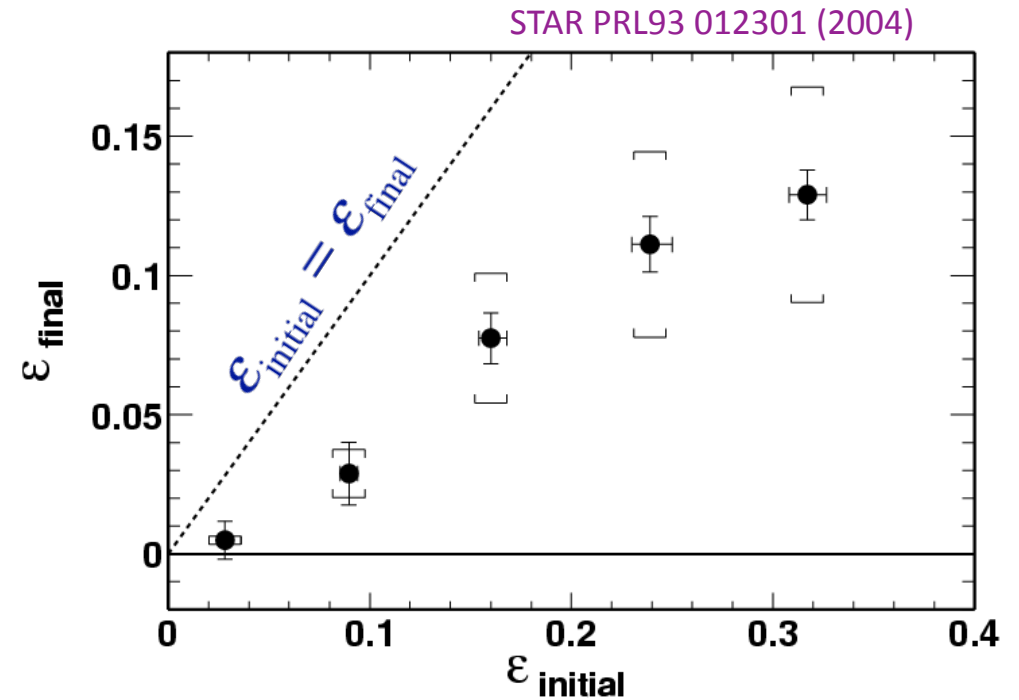
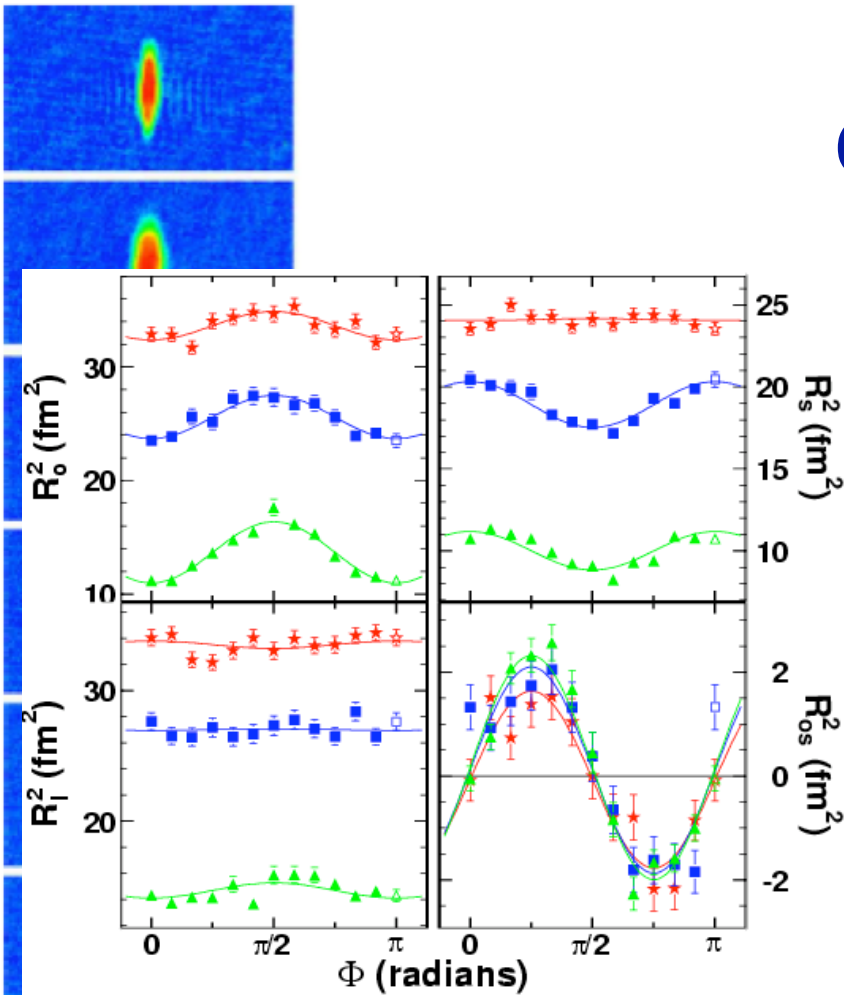
Homogeneity regions for pions moving to 0, 135 degrees

“No-flow formula” estimated good within ~ 30% (low pT)

$$R_{s,n}^2 \equiv \langle R_s^2(\phi) \cdot \cos(n\phi) \rangle \quad \epsilon \approx 2 \frac{R_{s,2}^2}{R_{s,0}^2} \approx 2 \frac{R_{os,2}^2}{R_{s,0}^2} \approx -2 \frac{R_{o,2}^2}{R_{s,0}^2}$$

Retiere&MAL PRC70 (2004) 044907

# “Spatial elliptic flow”: Centrality Evolution at RHIC

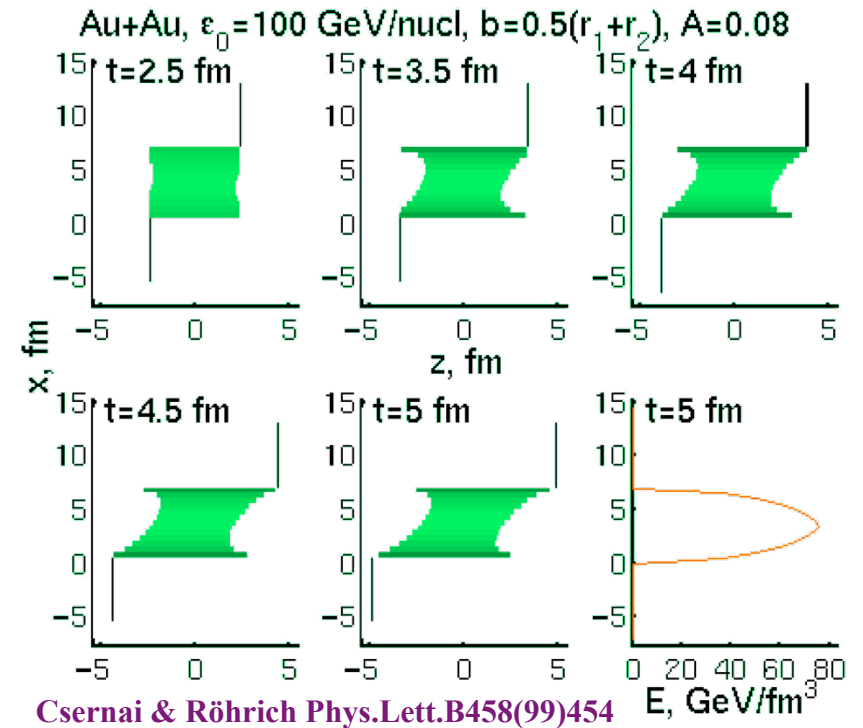
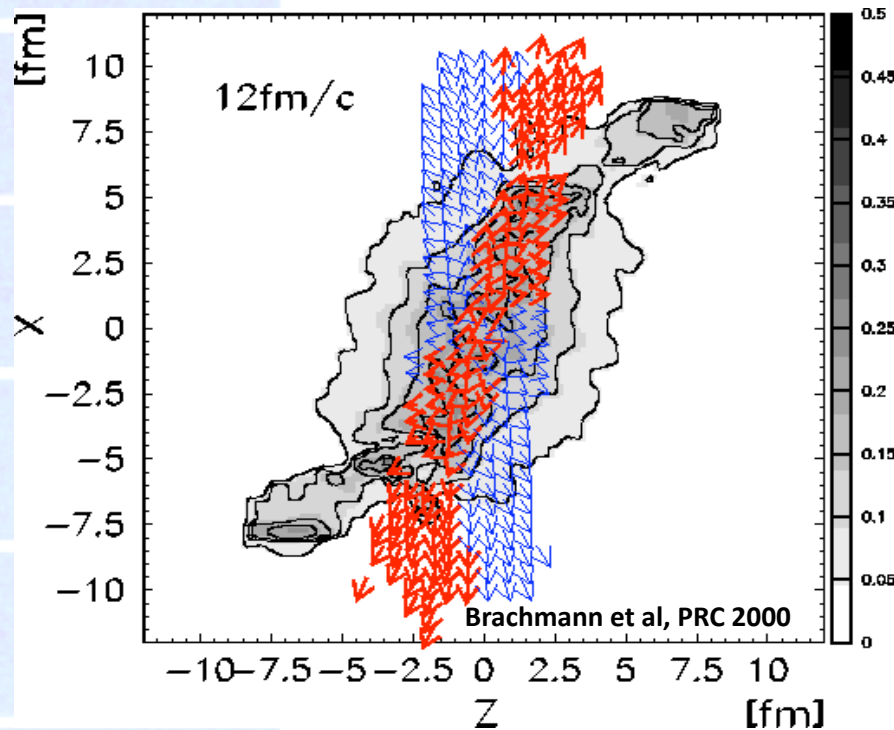


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Retiere&MAL PRC70 (2004) 044907

# Effects of “spatial *directed* flow?”

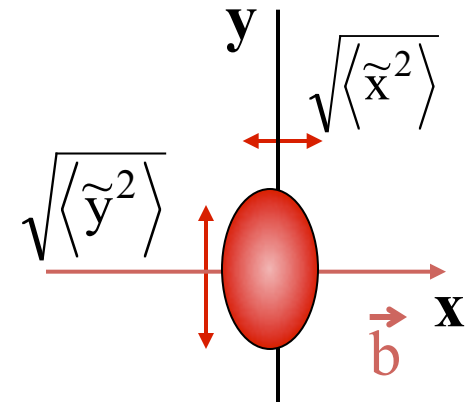
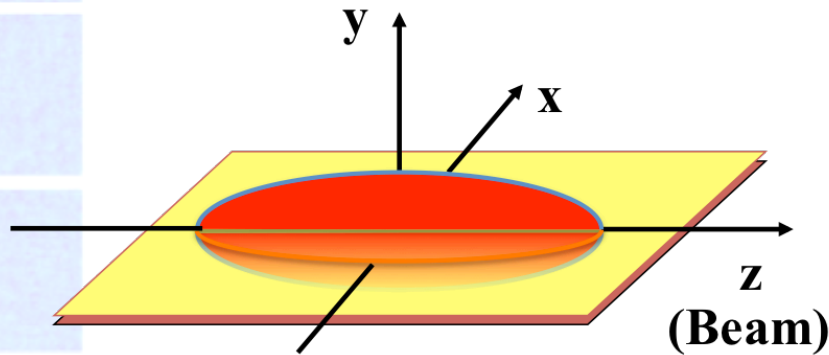


Csernai & Röhlich Phys.Lett.B458(99)454

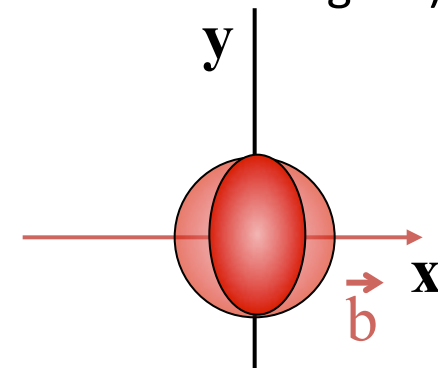
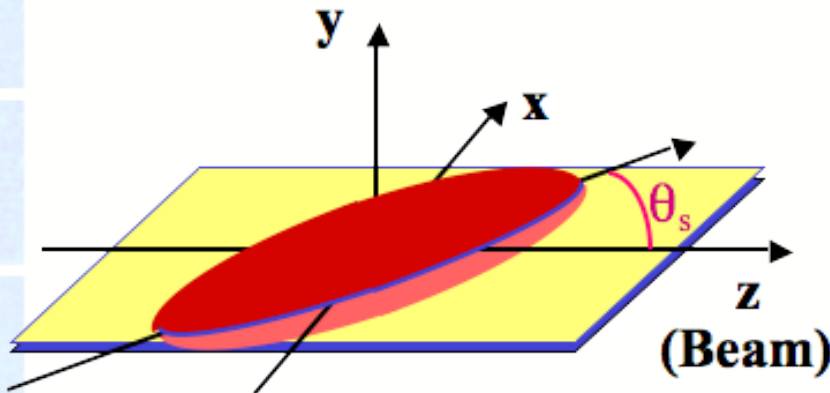
$$R_{s,n}^2 \equiv \langle R_s^2(\phi) \cdot \cos(n\phi) \rangle \quad \varepsilon \approx 2 \frac{R_{s,2}^2}{R_{s,0}^2} \approx 2 \frac{R_{os,2}^2}{R_{s,0}^2} \approx -2 \frac{R_{o,2}^2}{R_{s,0}^2}$$

Retiere&MAL PRC70 (2004) 044907

# Effects of “spatial *directed* flow?”



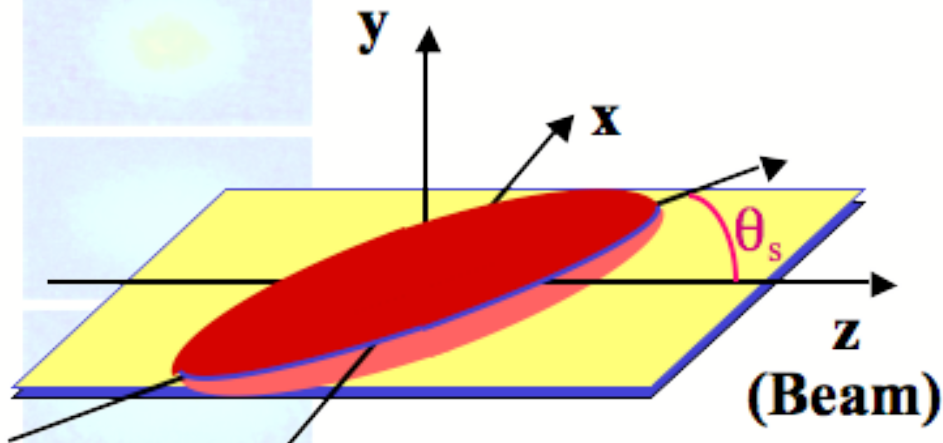
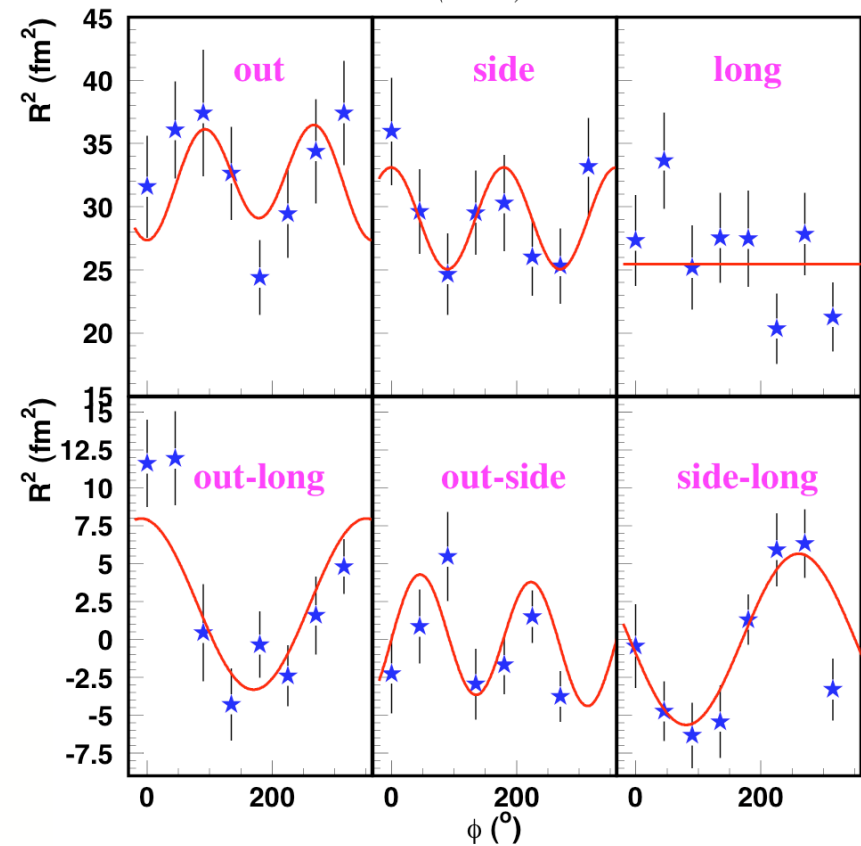
**Tilt angle  $\theta_s$**  – analog of “flow angle”  
 (... and “squeezeout” should be referenced to flow angle...)



$$R_{s,n}^2 \equiv \langle R_s^2(\phi) \cdot \cos(n\phi) \rangle \quad \epsilon \approx 2 \frac{R_{s,2}^2}{R_{s,0}^2} \approx 2 \frac{R_{os,2}^2}{R_{s,0}^2} \approx -2 \frac{R_{o,2}^2}{R_{s,0}^2}$$

# *first-order oscillations reveal large tilts @ AGS*

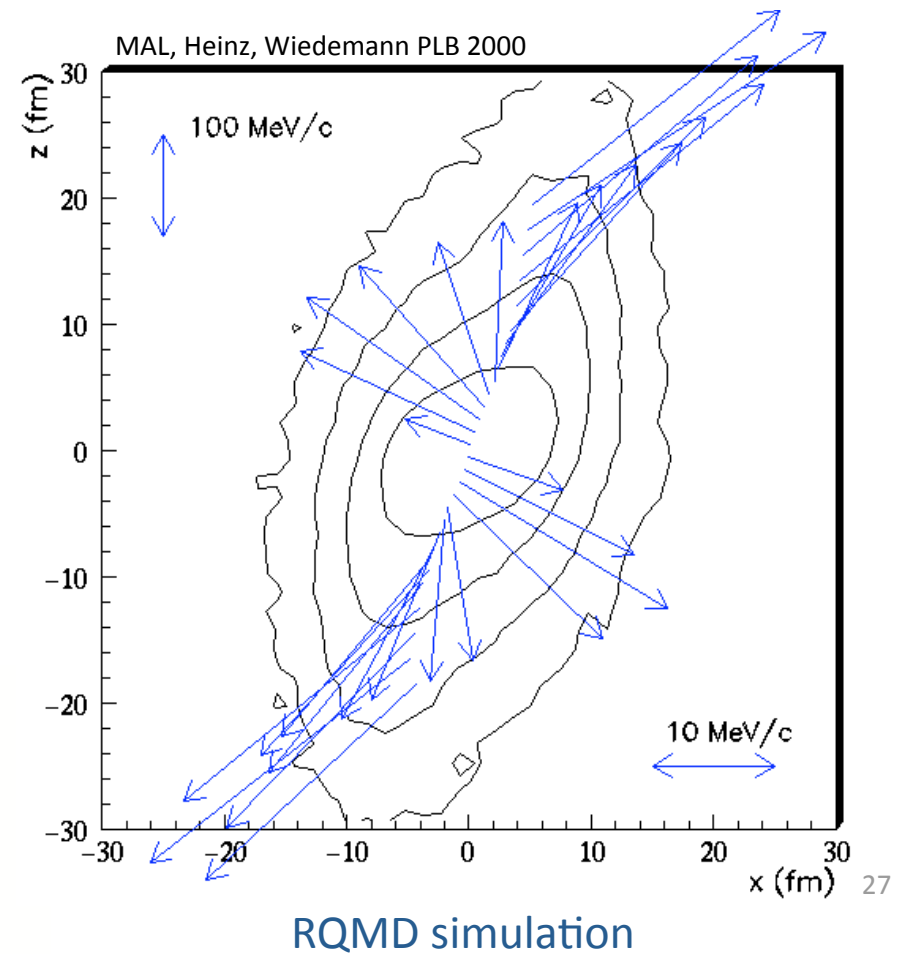
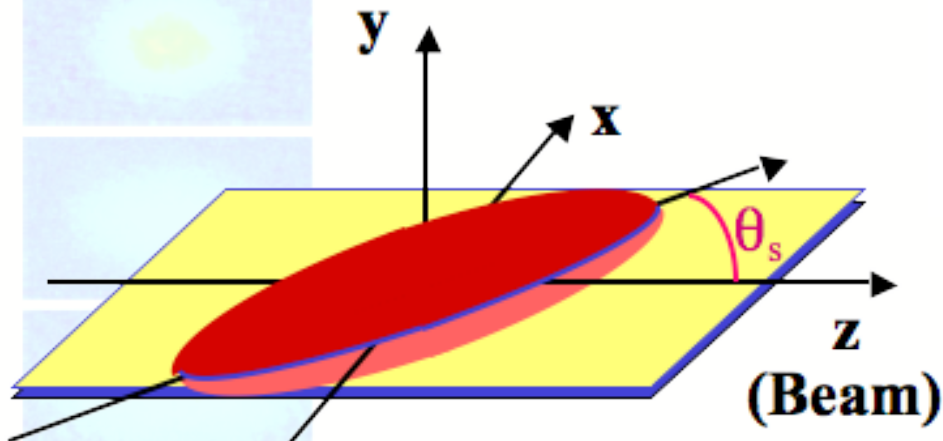
First-order R.P. needed



# *first-order oscillations reveal large tilts @ AGS*

First-order R.P. needed

Probed physics *behind* pion  
“anti-flow” (reflection, not  
absorption)



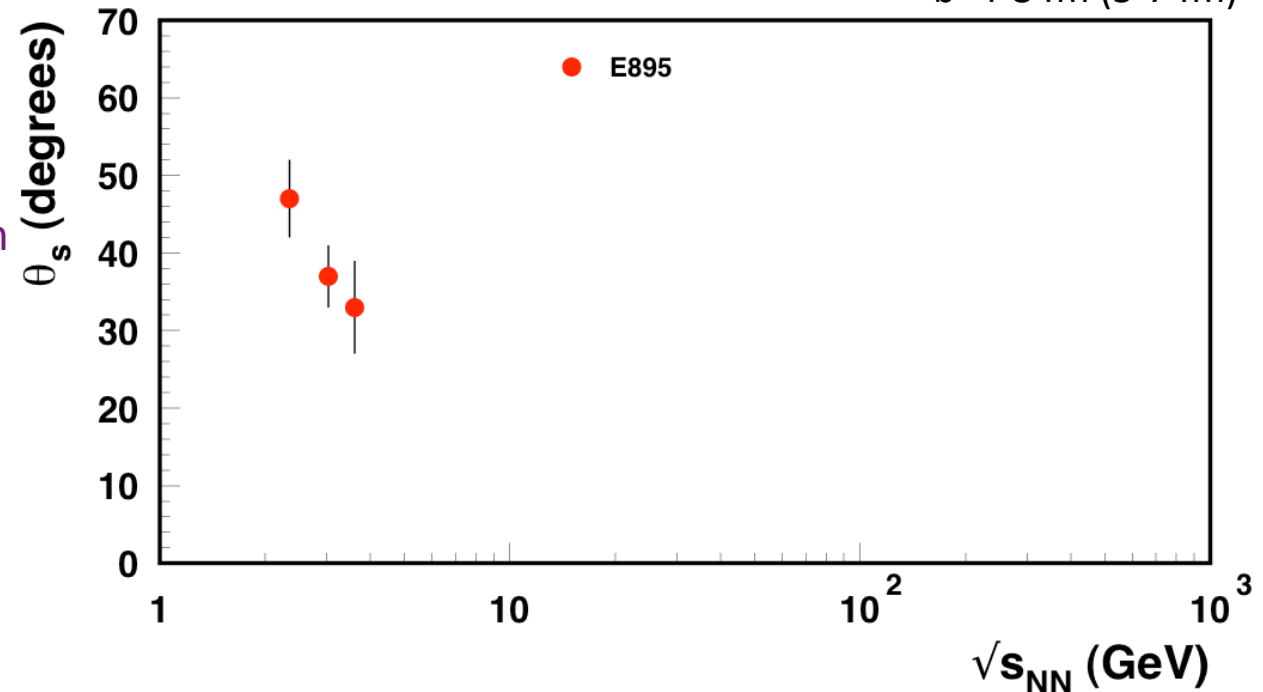
# models: large tilts @ AGS

$b=4-8$  fm (5-7 fm)

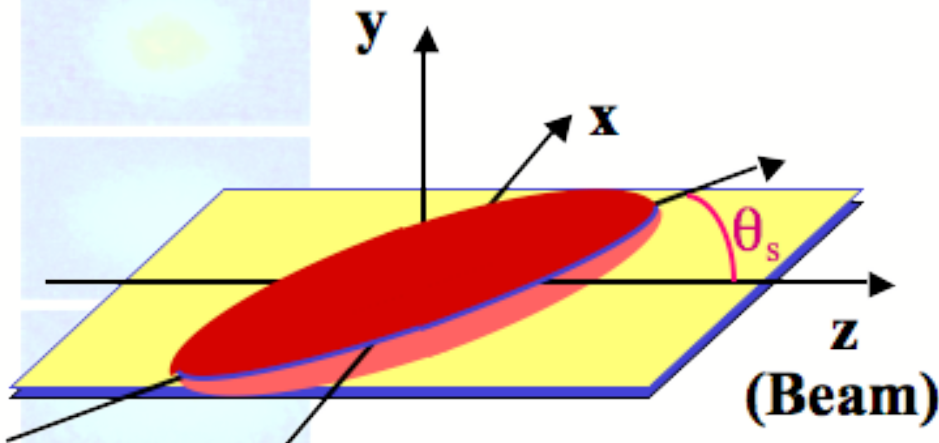
First-order R.P. needed

Probed physics *behind* pion  
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compare flow angle  $\sim 1^\circ$



- $\theta_s$  large, falls rapidly



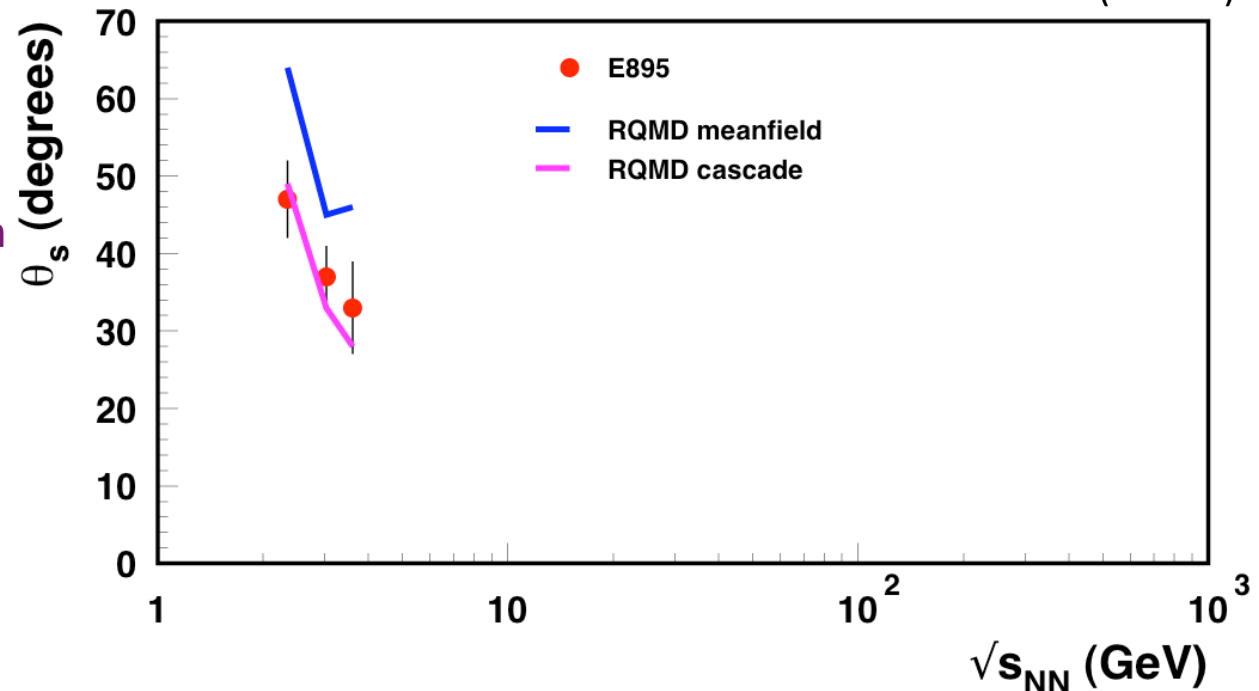
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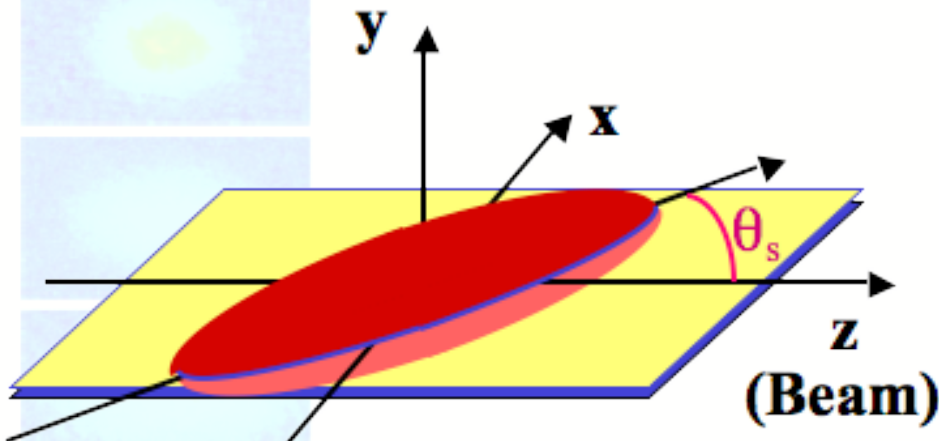
First-order R.P. needed

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compare flow angle  $\sim 1^\circ$



- $\theta_s$  large, falls rapidly
- spatial tilt disfavors mf, contrary directed flow



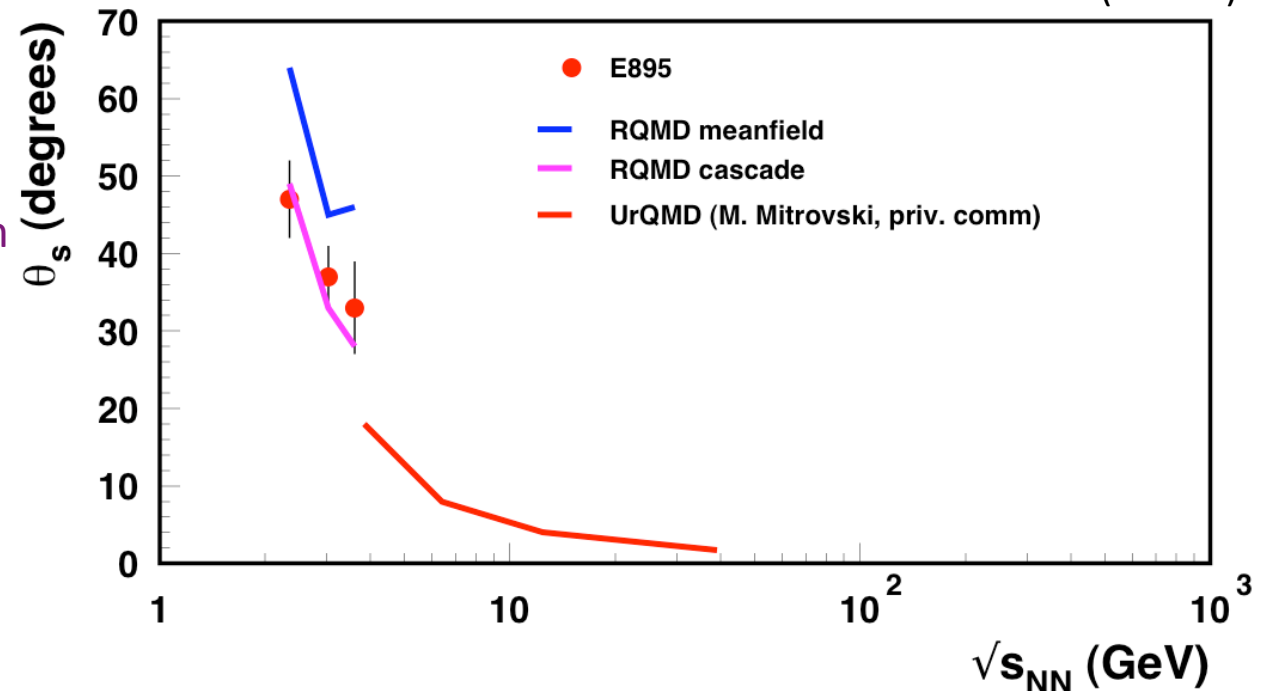
# models: large tilts @ AGS

$b=4-8$  fm (5-7 fm)

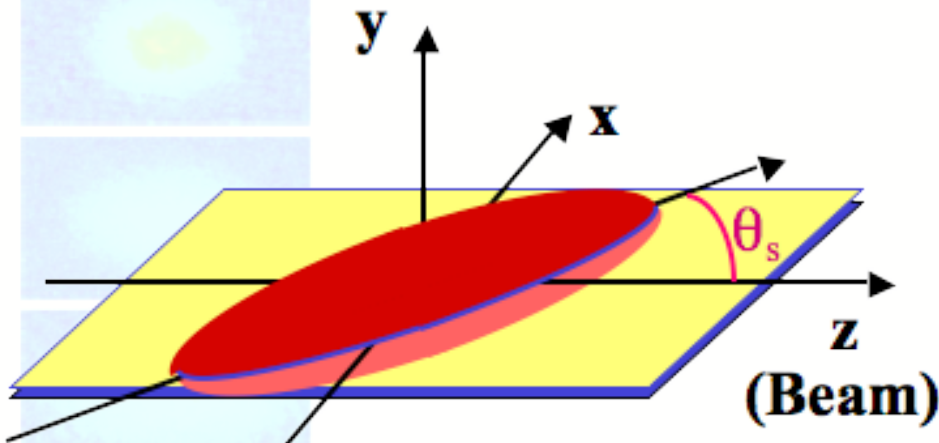
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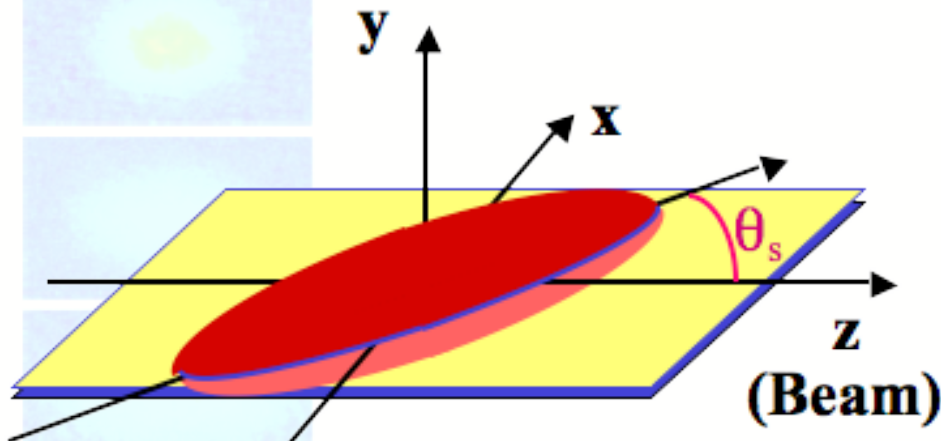
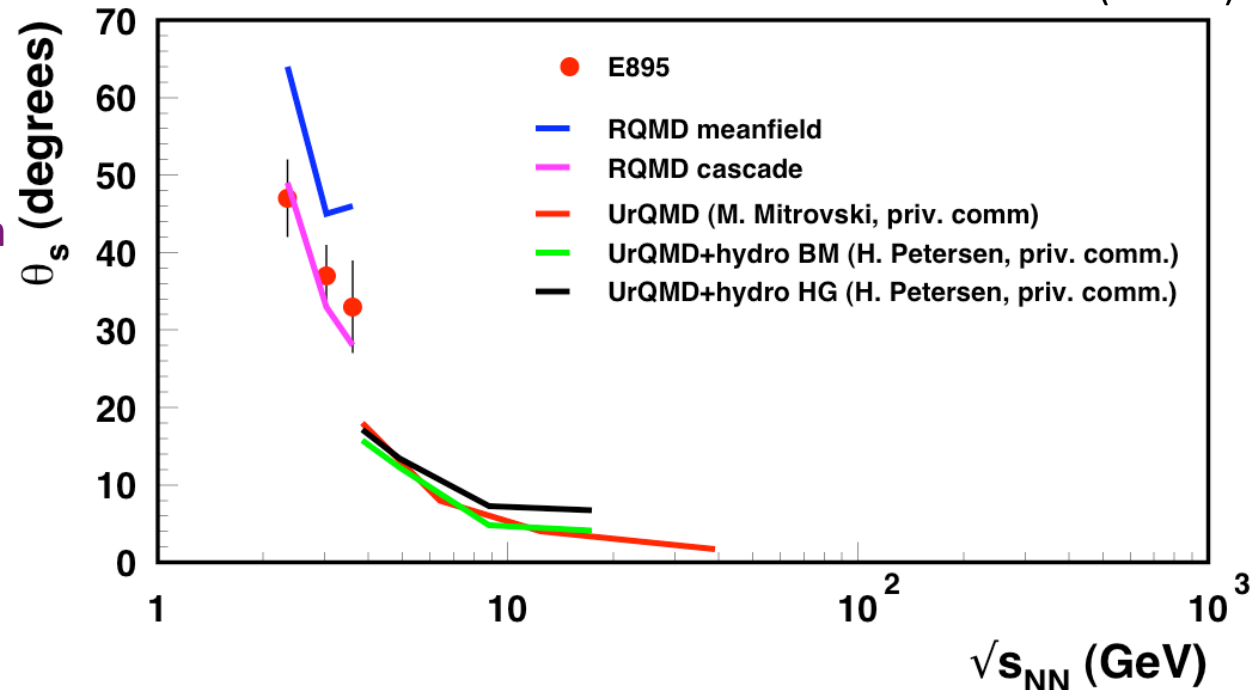
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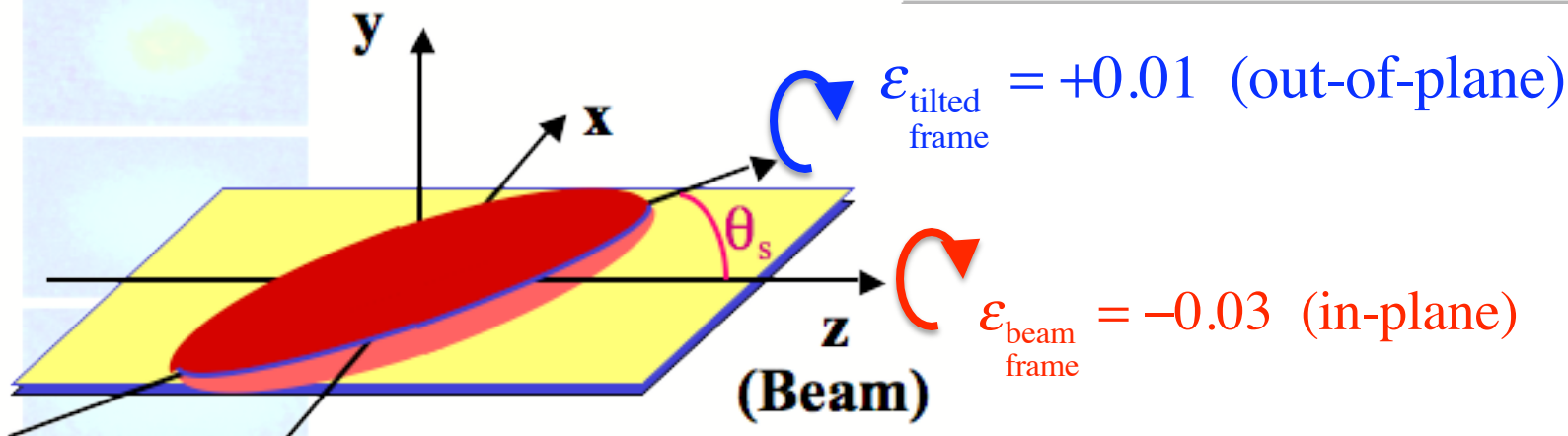
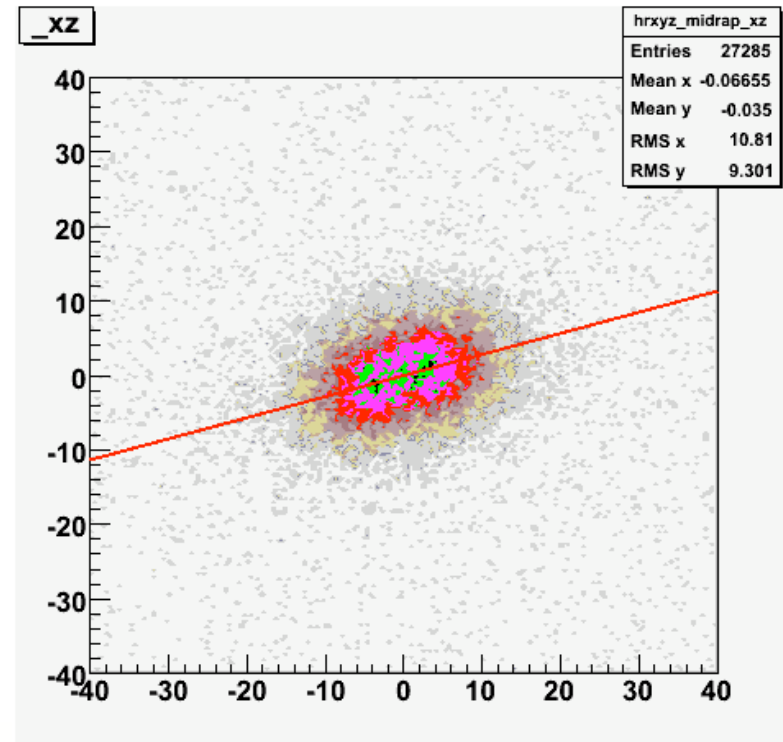
- $\theta_s$  large, falls rapidly
- spatial tilt disfavors mf, contrary directed flow
- significantly lower tilt (too low?) predicted by UrQMD & hybrids
- RHIC energies – probably negligible
  - 2D hydro OK?
- SPS?

# complications from large tilts?

## measurement:

UrQMD+hydro[BM]@ 3.8 GeV:

$\varepsilon$  in non-natural frame  
significantly reduced from  $\varepsilon$  in  
natural (tilted) frame  
affects CERES measurement?



# complications from large tilts?

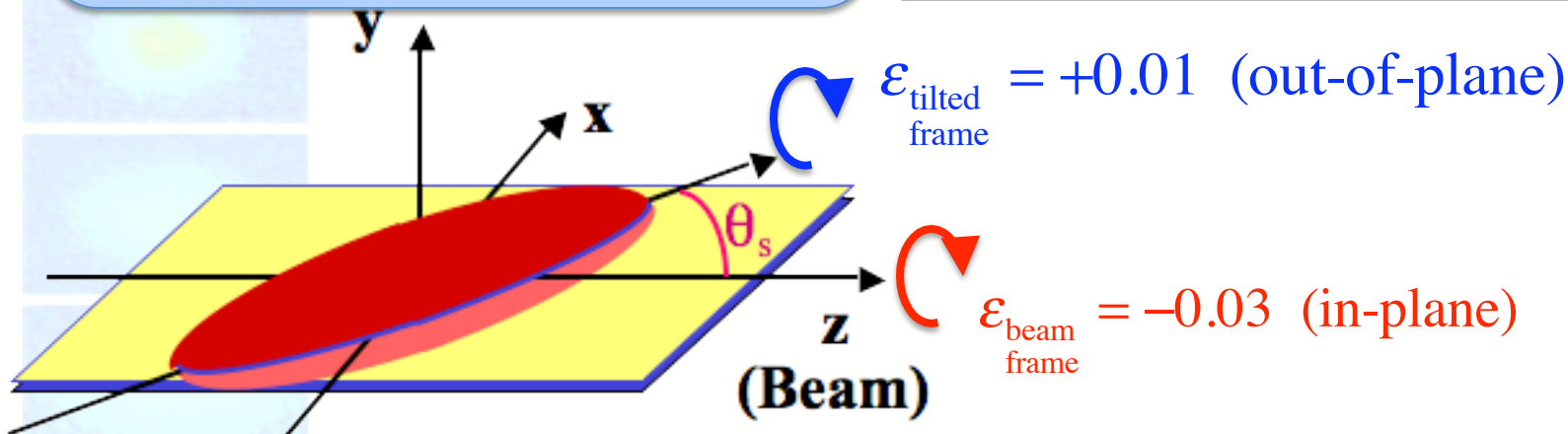
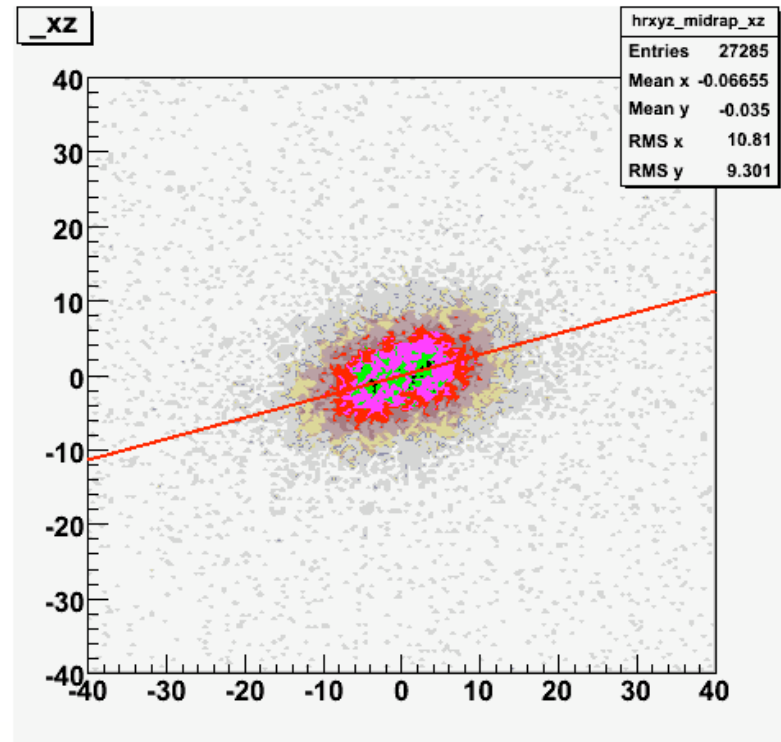
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UrQMD+hydro[BM]@ 3.8 GeV:

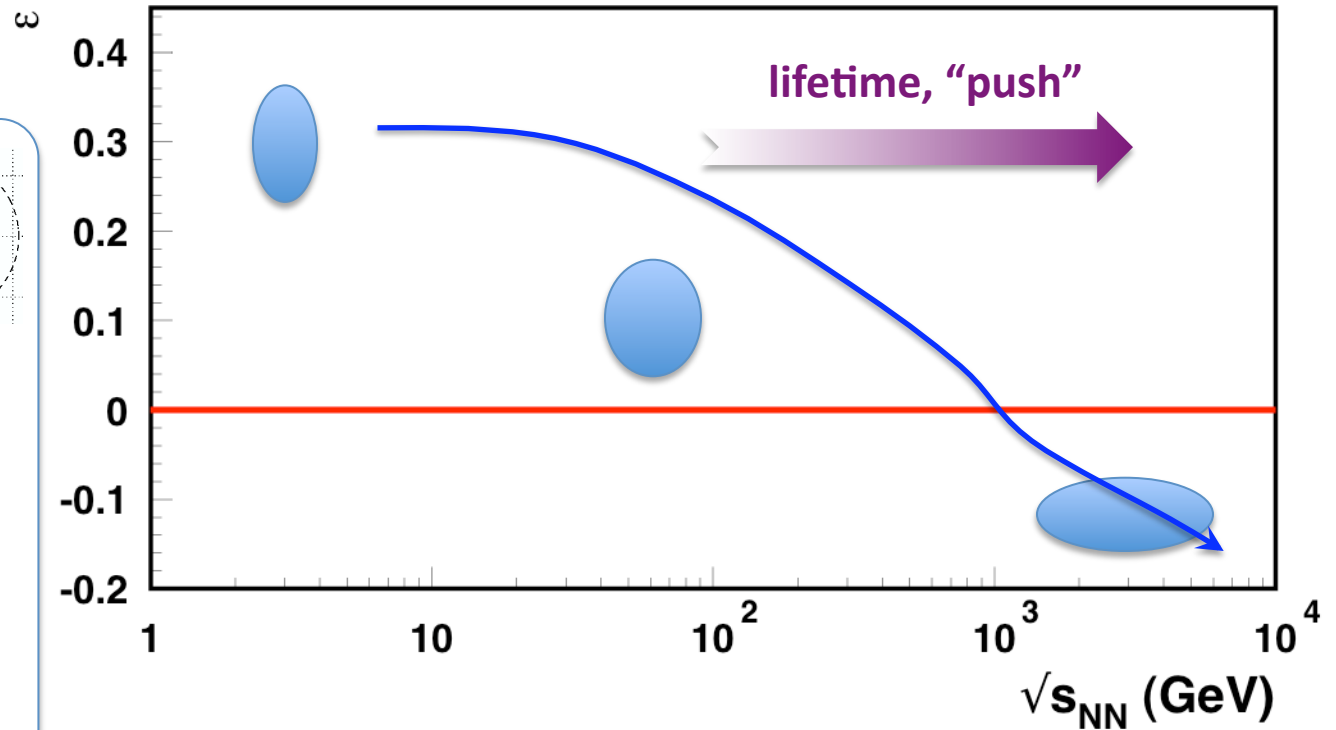
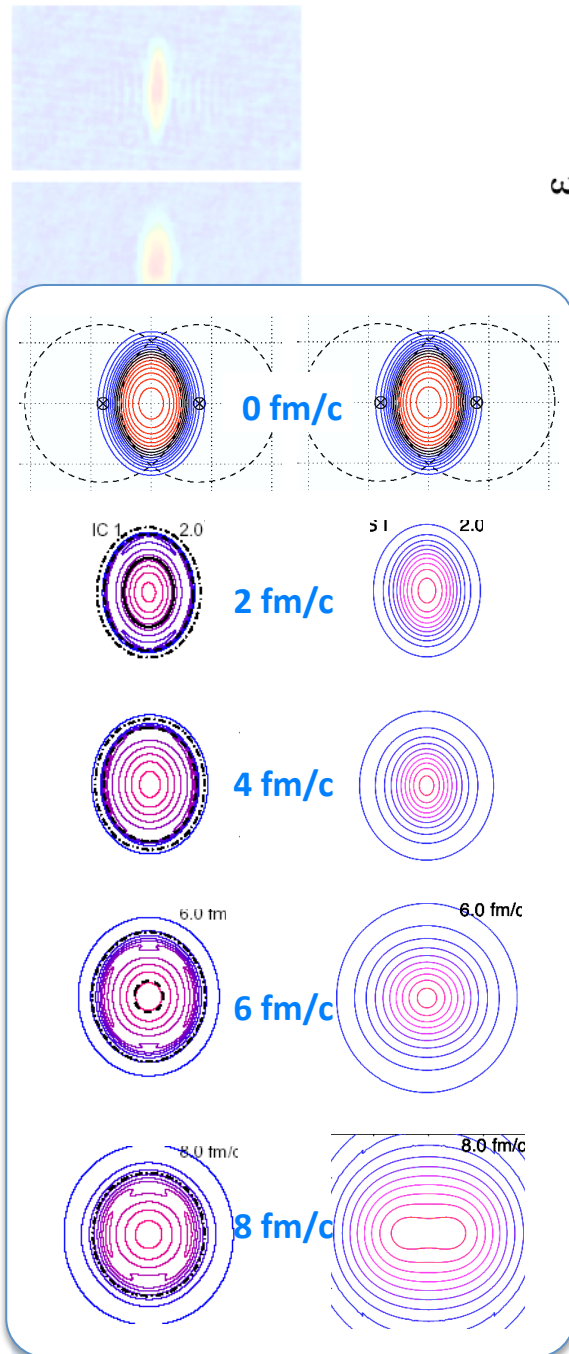
$\varepsilon$  in non-natural frame  
significantly reduced from  $\varepsilon$  in  
natural (tilted) frame  
affects CERES measurement?

## transport

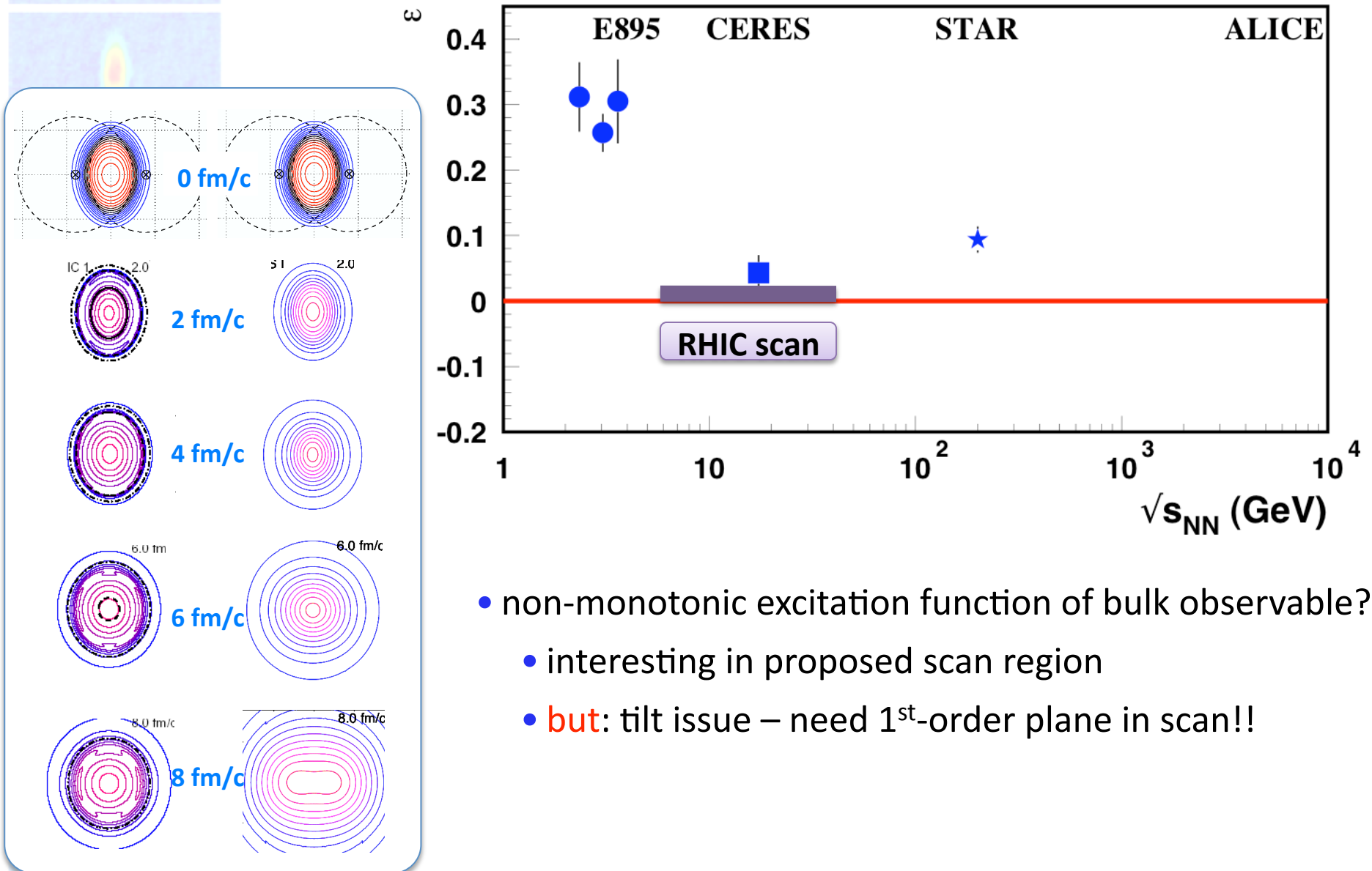
Tilts are manifestly “boost variant,”  
in *space* even *at*  $y=0$   
2D hydro codes?



# Generic expectation

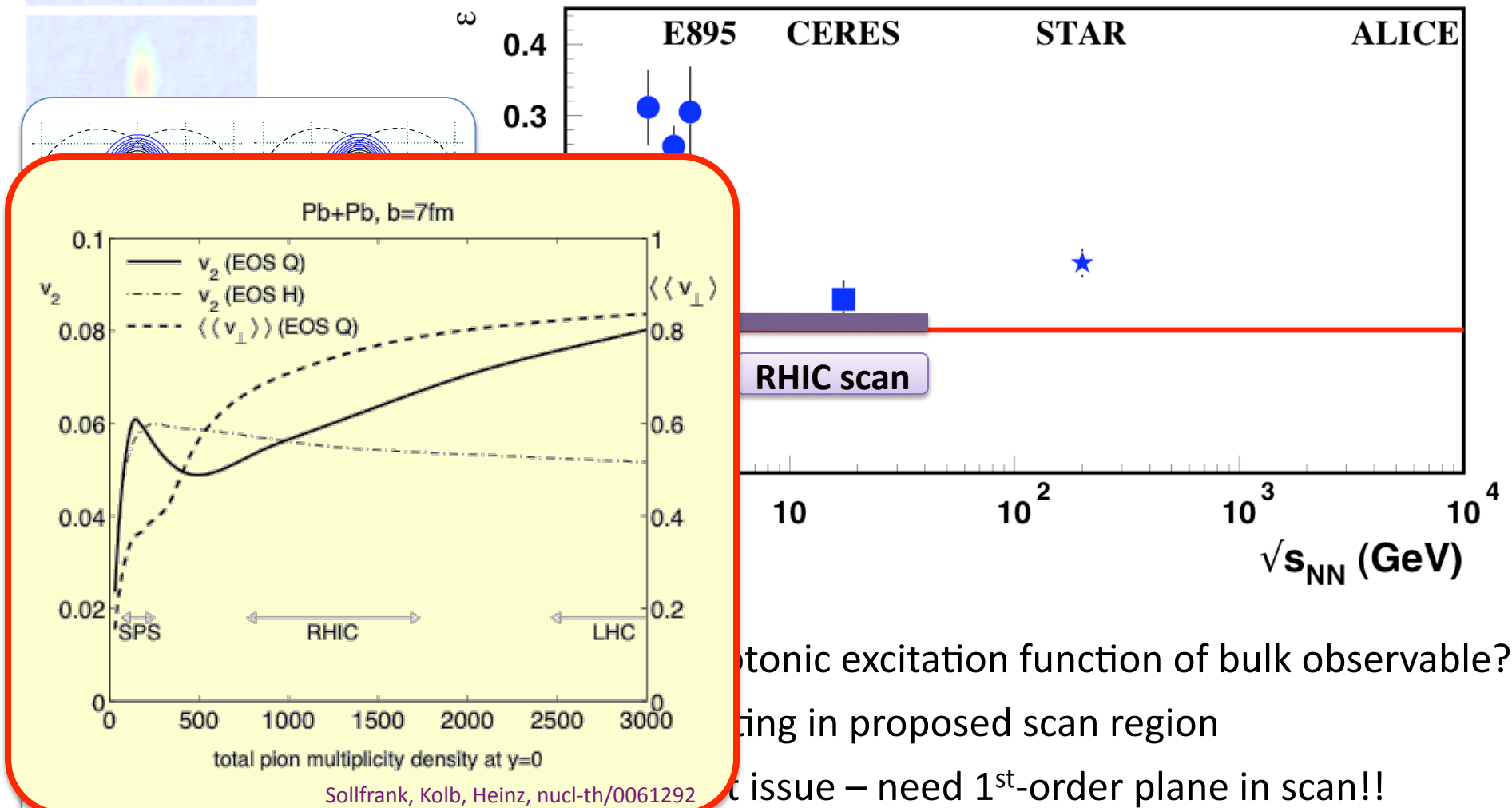


# An excitation function begging for more



- non-monotonic excitation function of bulk observable?
  - interesting in proposed scan region
  - **but**: tilt issue – need 1<sup>st</sup>-order plane in scan!!

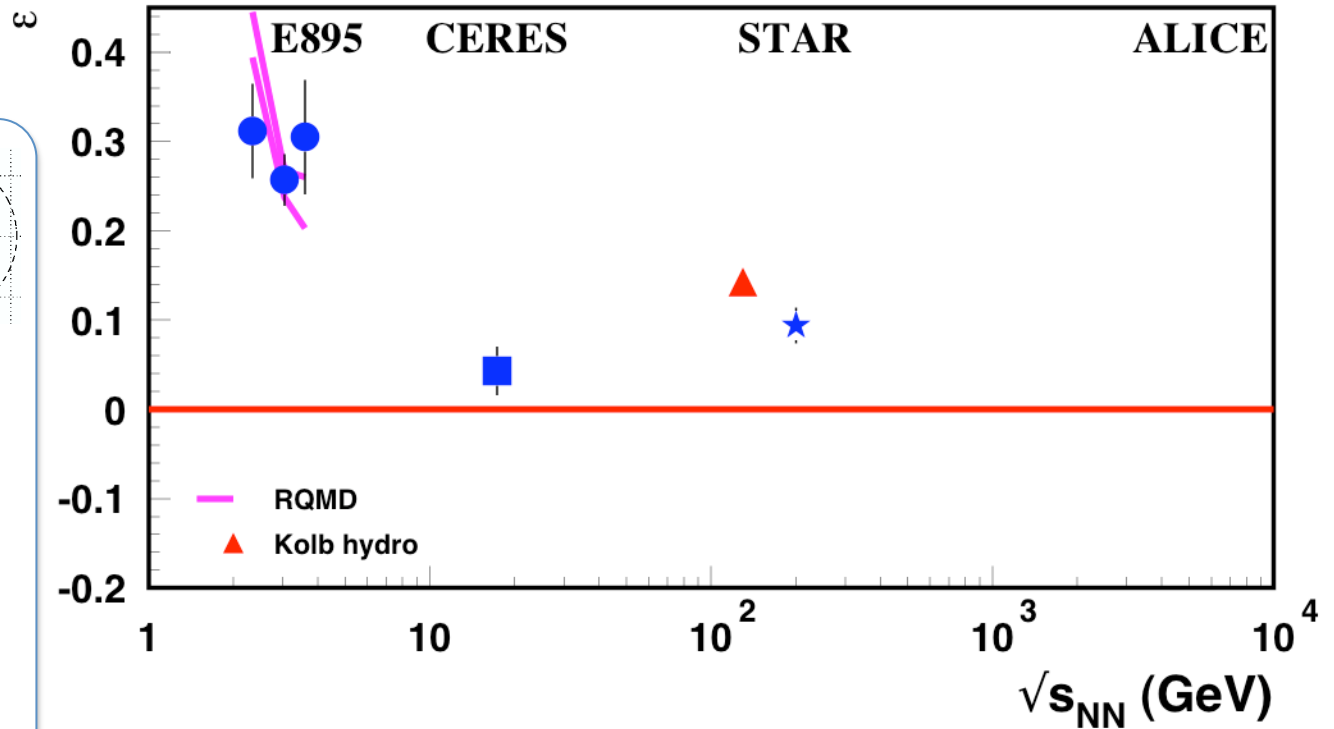
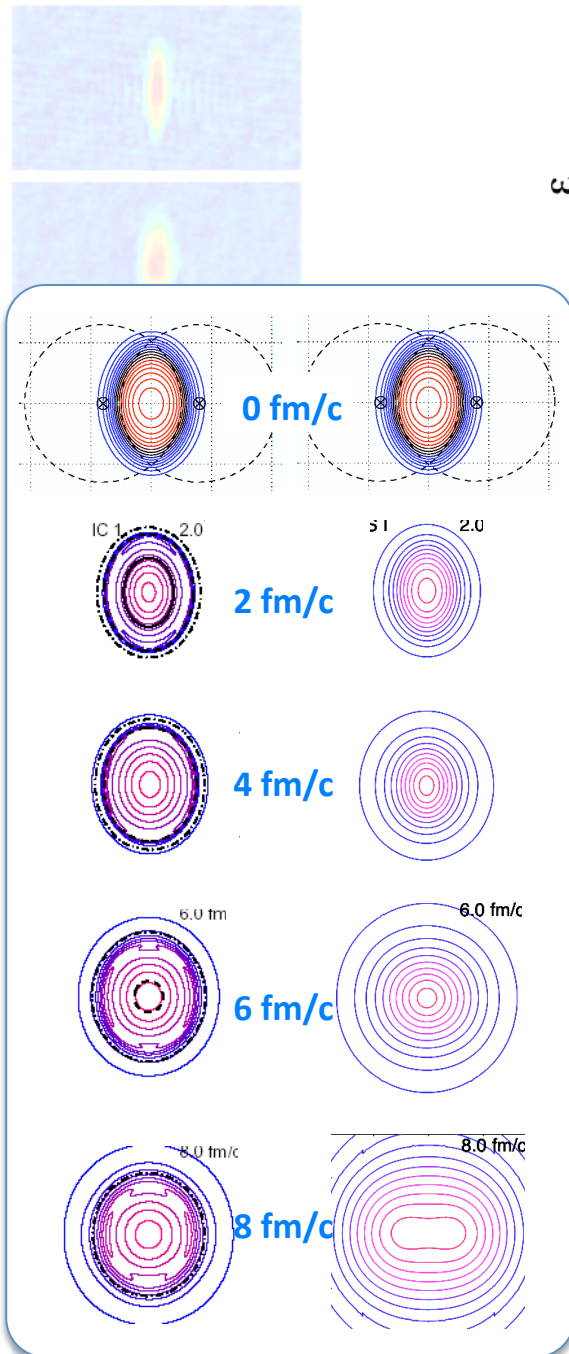
# An excitation function begging for more



tonic excitation function of bulk observable?  
 ing in proposed scan region  
 t issue – need 1<sup>st</sup>-order plane in scan!!

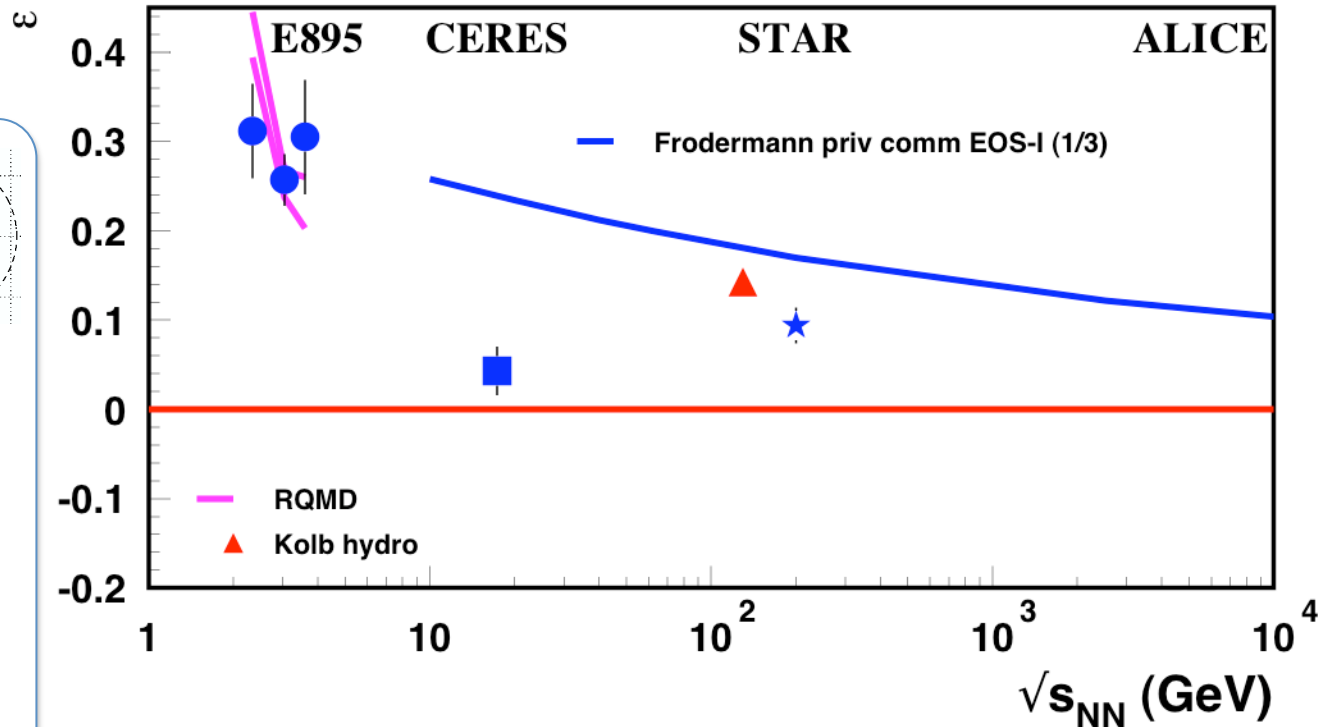
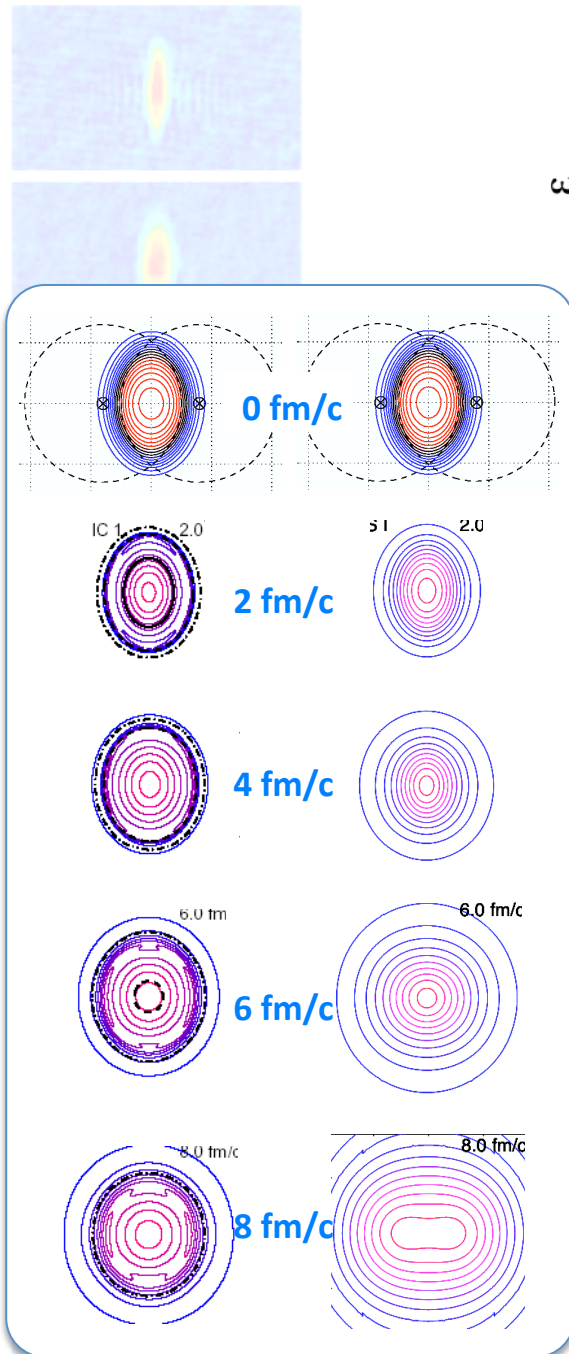
- reminiscent of (unobserved) non-monotonic  $v_2(\sqrt{s})$

# Model comparisons



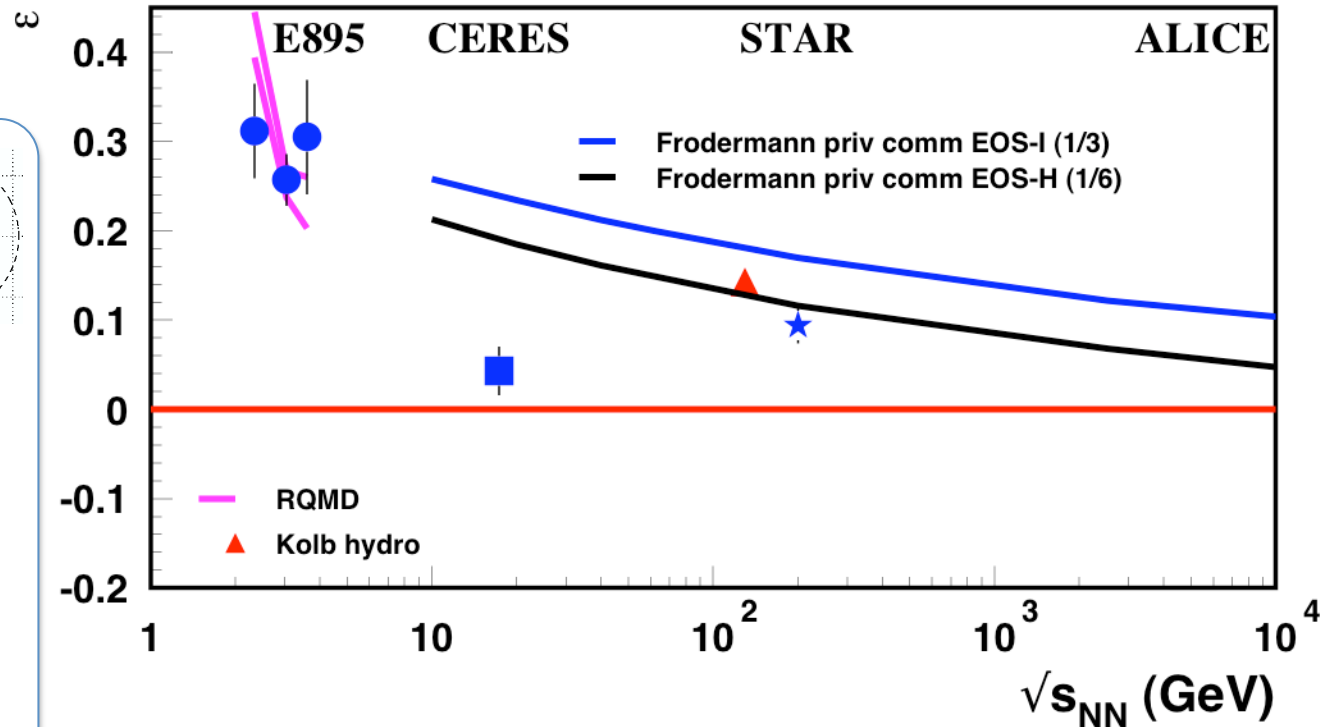
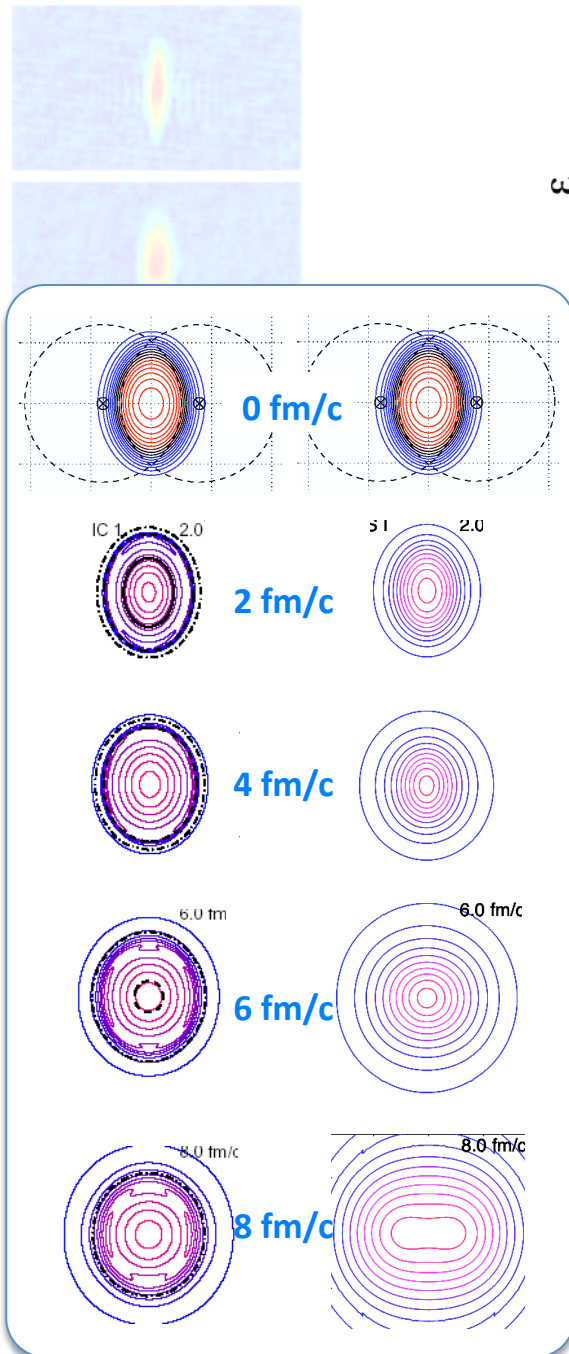
- ✓ RQMD (not UrQMD) @ low energy
- ✓ 2D hydro of Kolb/Heinz @ RHIC

# effect of EoS – 2D hydro



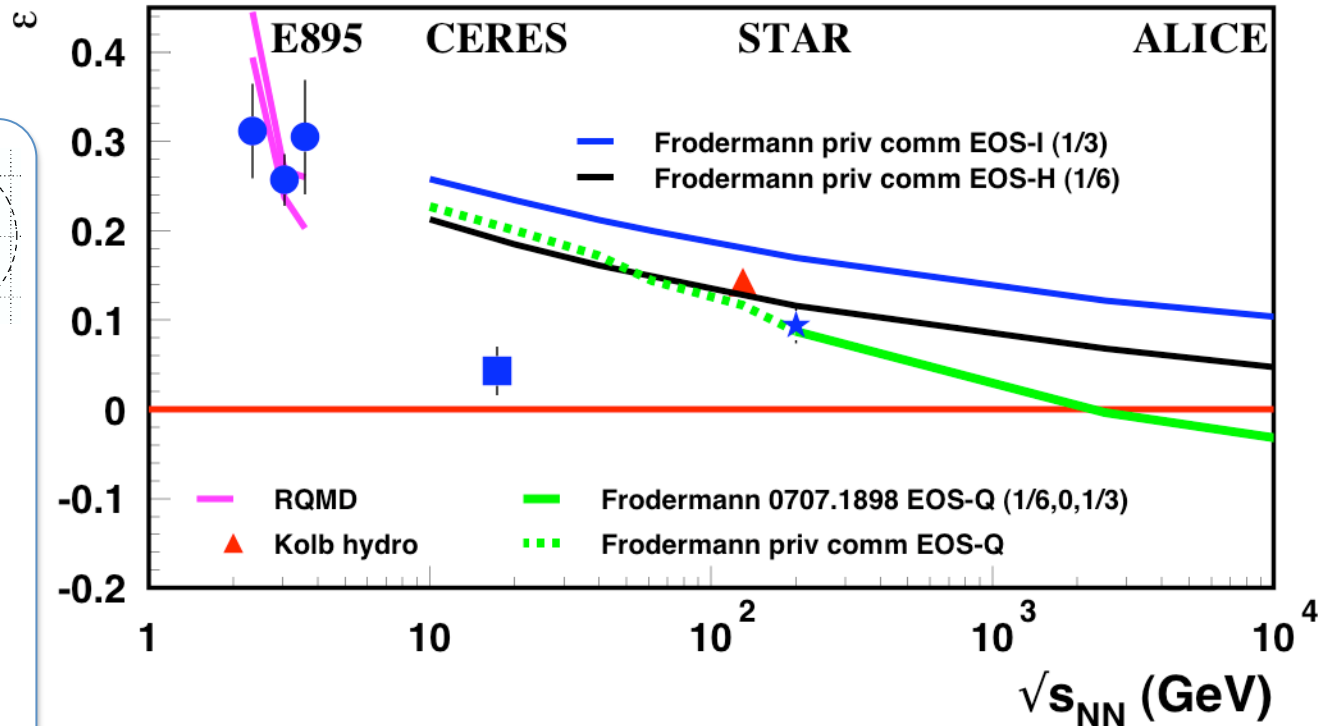
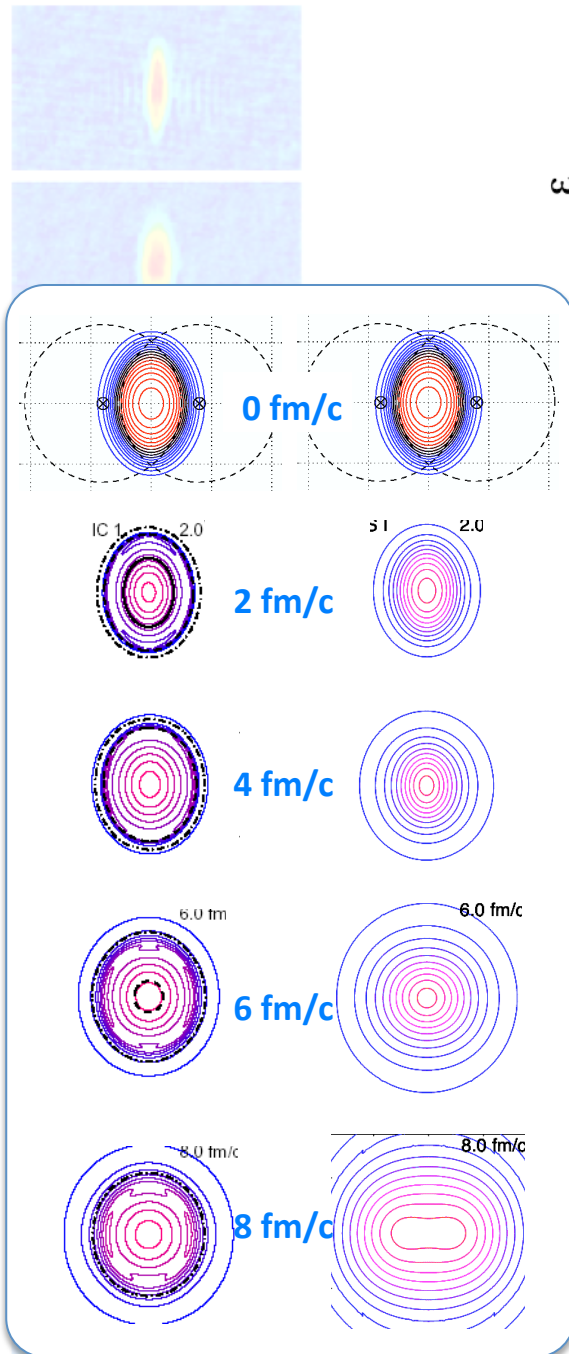
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- scan with varying EoS 2D hydro

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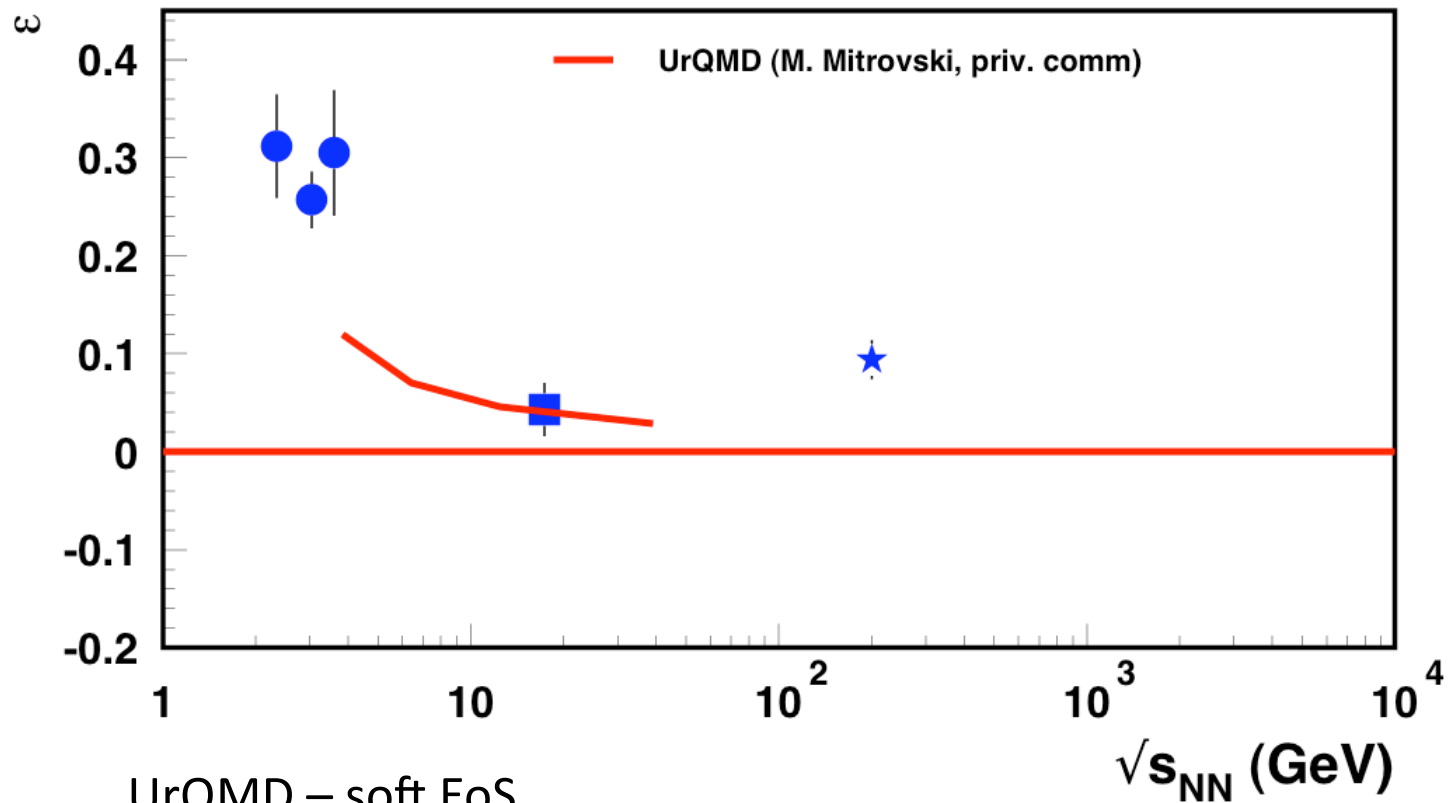
- ✓ RQMD (not UrQMD) @ low energy
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# effect of EoS – 2D hydro



- ✓ RQMD (not UrQMD) @ low energy
- ✓ 2D hydro of Kolb/Heinz @ RHIC
- scan with varying EoS 2D hydro
  - expected dependence on stiffness
  - no non-monotonic behaviour predicted
  - **but**: 2D boost-invariant – no tilt

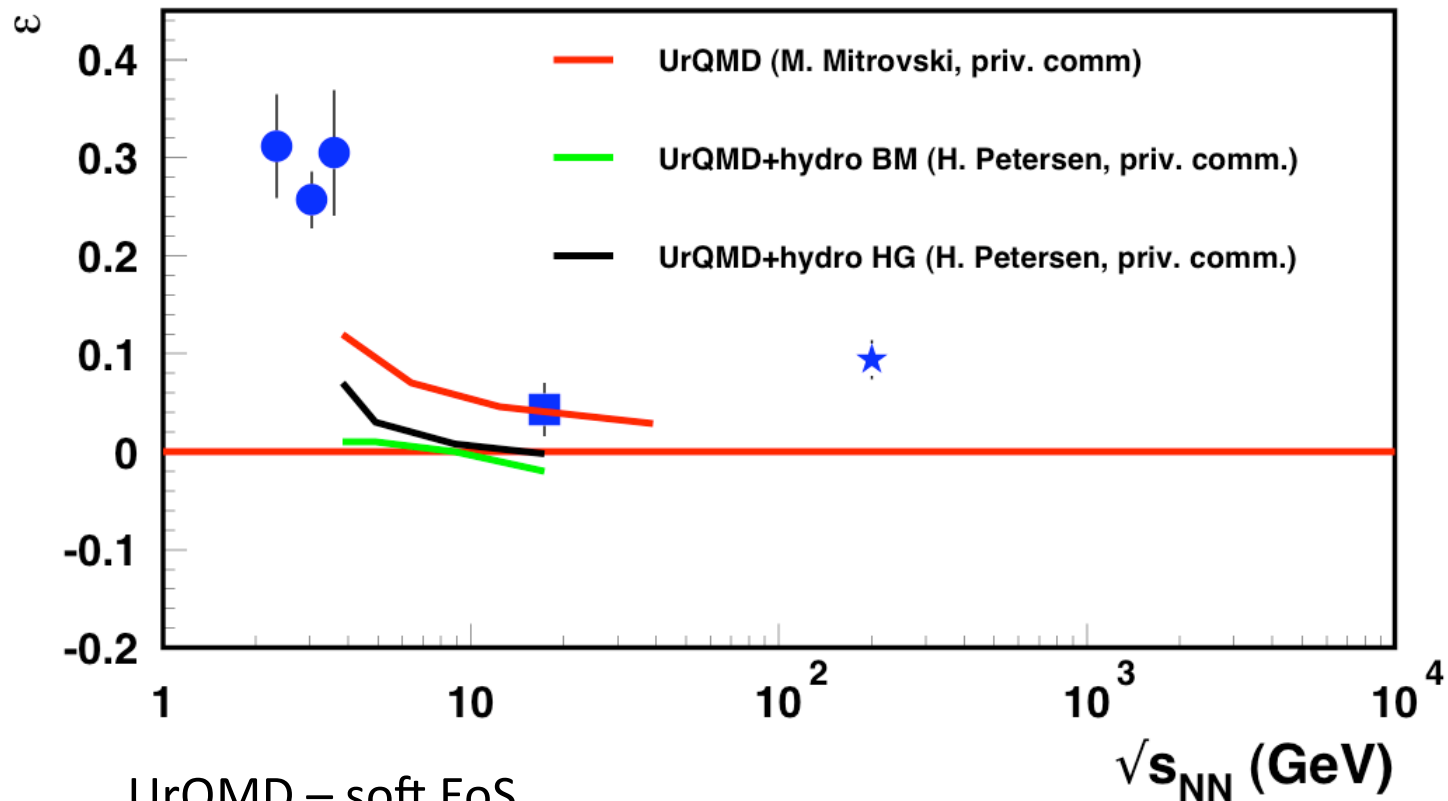
# 3D transport



UrQMD – soft EoS

- ✓ reproduces CERES' anisotropy
- root(s) dependence looks unlikely

# 3D transport

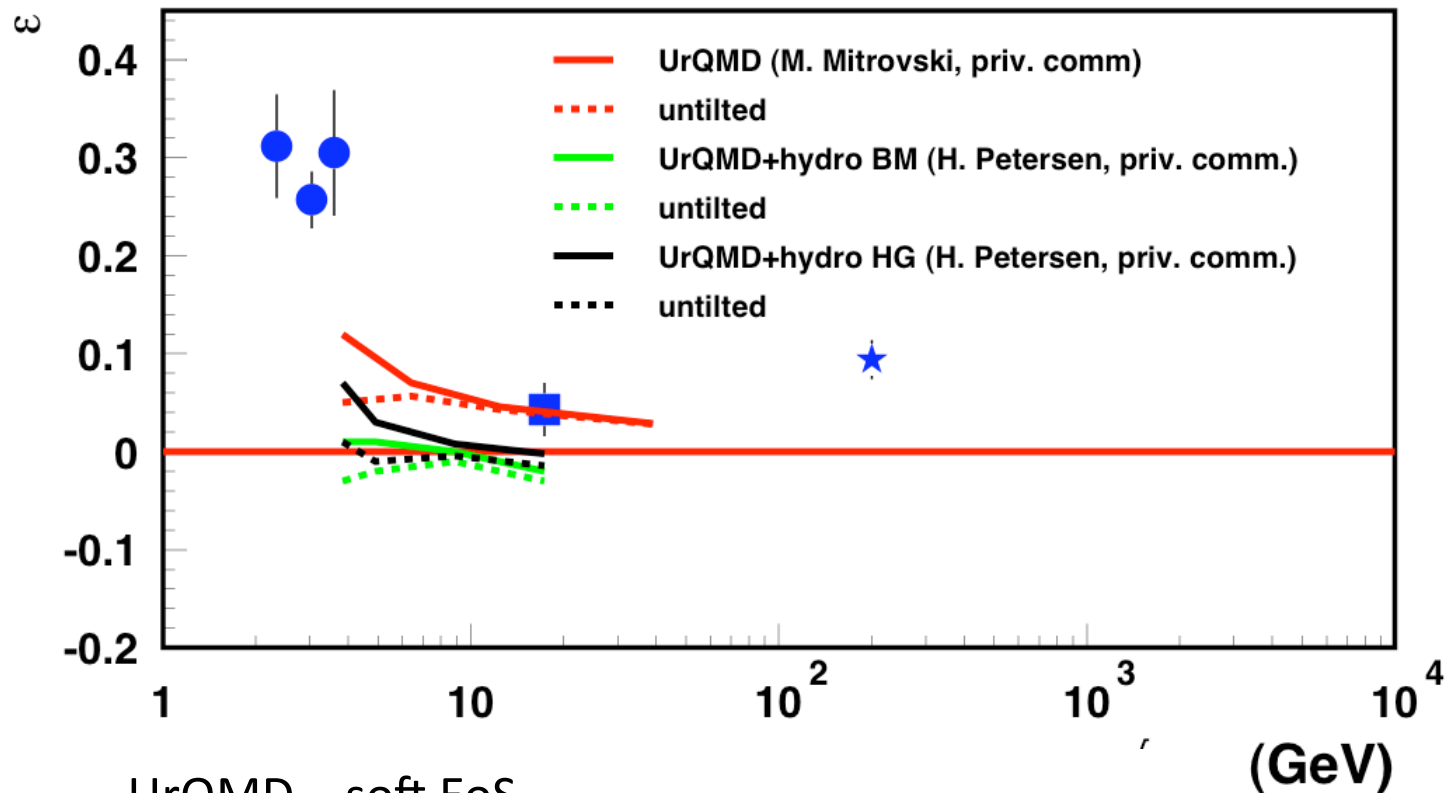


UrQMD – soft EoS

- ✓ reproduces CERES' anisotropy
- root(s) dependence looks unlikely

hybrid models: long-lived system evolves to round

# 3D transport



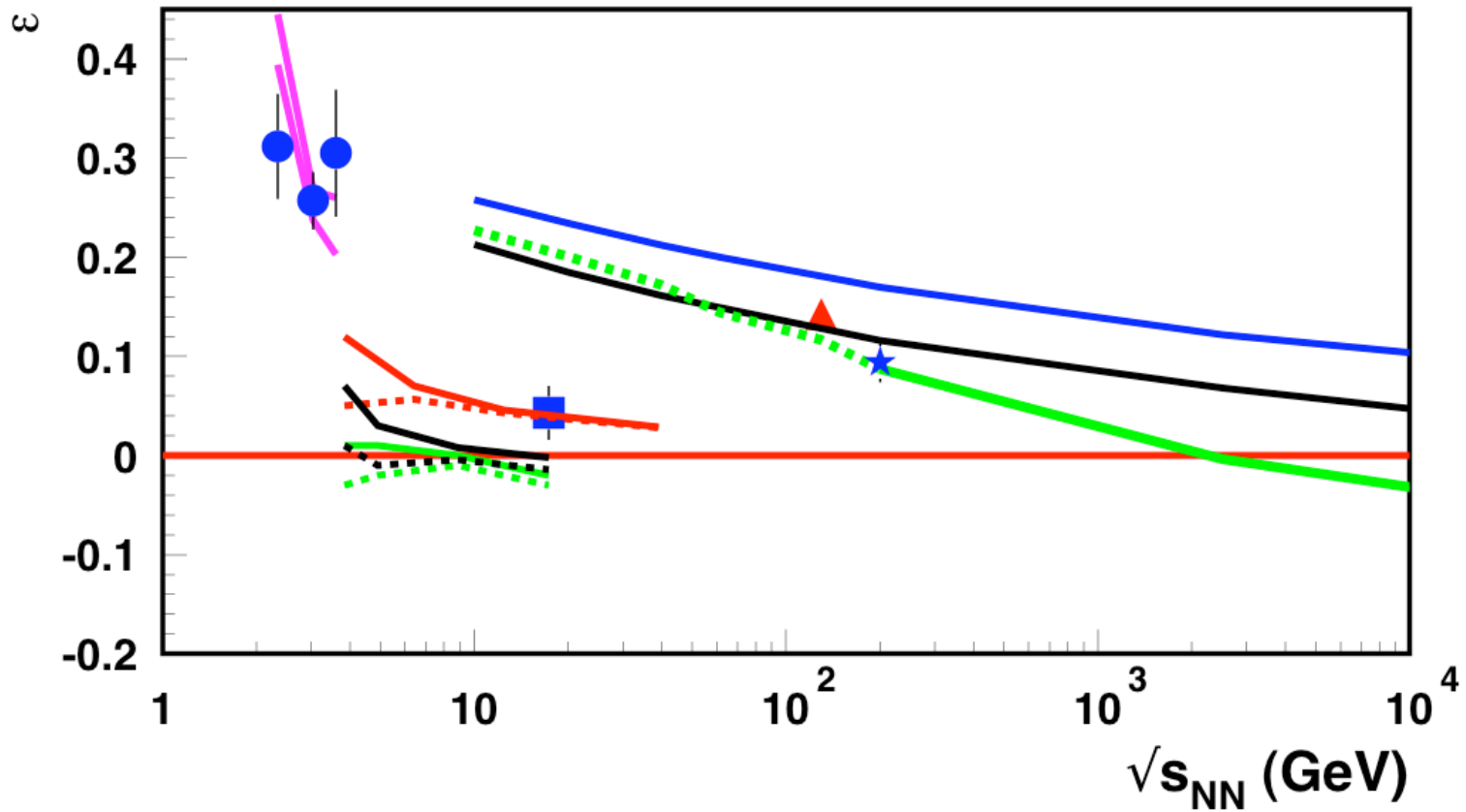
UrQMD – soft EoS

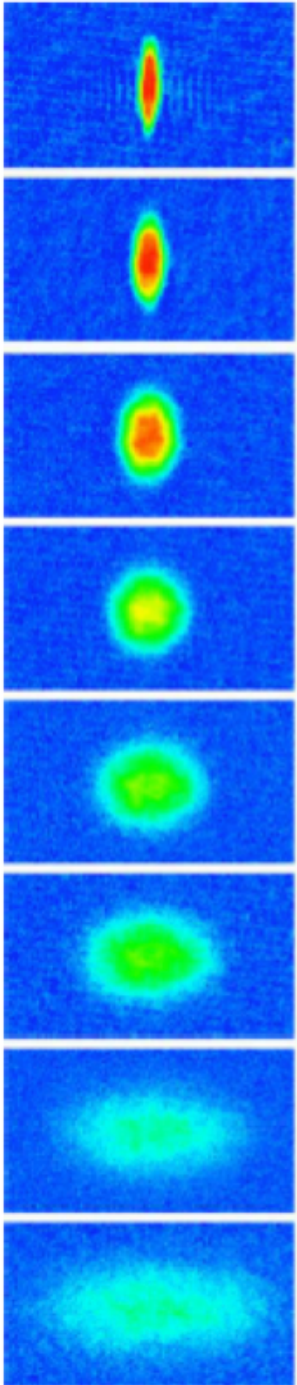
- ✓ reproduces CERES' anisotropy
- root(s) dependence looks unlikely

hybrid models: long-lived system evolves to round

\* tilt not important (because  $\theta$  and  $\varepsilon$  both small)

# Unified description of shape evolution?





## how to spend ½ hour discussing 5 data points

- **p**-dep femtoscopy reveals flow-generated substructure
- asHBT measures detailed spatial analogs of  $v_1$ ,  $v_2$
- bulk observable with
  - sensitivity to EoS & dynamical time (& 3<sup>rd</sup> flow component, early softening...?)
  - non-monotonic excitation function:  
interesting feature @ “interesting” energy  
asHBT part of B.E.S. program
- true 3D, unified modeling important, to map out spatial dynamics
- 1<sup>st</sup>-order R.P. necessary during RHIC energy scan
- much more work on experimental and theoretical/modeling side



# asHBT model calculations- *THANKS!*

- **P. Kolb** [Regensburg, Ohio] – 2D hydro EOS-Q @ 130 GeV
- **E. Frodermann** [Minnesota]– 2D hydro EOS-Q, EOS-I, EOS-H, 10 GeV - 300 TeV
- **M. Mitrovski & M. Bleicher** [Frankfurt] – UrQMD,  $\sqrt{s} = 4\text{-}39$  GeV
- **M. Lisa** [Ohio] – RQMD meanfield on/off  $\sqrt{s} = 2\text{-}4$  GeV
- **H. Petersen** [Frankfurt] – UrQMD + 3D hydro,  $\sqrt{s}=4 - 17$  GeV, BM & HG EoS

See also:

- A. Kisiel et al – hydro+Therminator: PR **C79** 014902 (2009)
- T. Humanic – hadronic rescattering (HRM): Int.J.Mod.Phys.**E15**, 197 (2006)
- D. Teaney, J. Lauret, & E. Shuryak – RQMD & hybrid - nucl-th/0110037